LIFE CYCLE ASSESSMENT OF THE PRODUCTION OF CEMENT:

A SOUTH AFRICAN CASE STUDY

Submitted in fulfillment of the requirements for the degree of

Master of Engineering

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and the Built Environment

By

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Date: 24th June, 2021

DECLARATION

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DEDICATION

This research is dedicated to God, who has been my source of inspiration from the beginning to the end of this work.

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The journey so far has been a combination of highs and lows, but in all, this dissertation serves as evidence of triumph which would not have been possible without the academic, emotional, financial, moral, professional, social and spiritual support of the following people:

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SIYABONGA ZONKE!

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS/ ACRONYMS

AAC	Activated cements and concretes
AFs	Alternative fuels
AoSL	Area of significance to life
AR	Alternative resource
AS	Alternative scenario
BAT	Best available technique
BREF	Best Available Techniques Reference Document
BS	Biological sludge
CCS	Carbon capture and storage
CKD	Cement kiln dust
DALY	Disability adjusted life years
DCB	Dichlorobenzene
EIPPCB	European Integrated Pollution Prevention and Control Bureau
Eq	Equivalent
GDP	Gross Domestics Product
GHG	Greenhouse gas
GT	Giga tonnes
GGBFS	Ground granulated blast furnace slag
GWP	Global warming potential
HH	Human health
IFC	International Finance Corporation
IFA	Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung
ILCD	International Reference Life Cycle Data System
IMF	International Monetary Fund
IPCC	Integrated Pollution Prevention and Control
ISO	International Standard Organization

LCA	Life cycle assessment
LCC	Life cycle costing
$LCCO_2$	Life cycle CO_2
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MT	Million/ Mega tonnes
NGO	Non-government organization
NMVOC	Non-methane volatile organic compound
OPC	Ordinary Portland cement
PPC	Pretoria Portland cement
PPM	Part per million
RDF	Refuse derived fuel
ReCiPe	RIVM and Radboud University, CML and PRé Consultants
SSA	Sub-Saharan Africa
SCMs	Supplementary cementing materials
SNCR	Selective non-catalytic reduction
SETAC	Society of environmental toxicology and chemistry
TE	Terrestrial ecosystem
TDF	Tyre derived fuel
Tons	Tonnes
TS	Traditional scenario
UNFCC	United Nations Framework Convention on Climate Change
UNEP	United Nations Environment Programme
USGS	United State Geological Society
UV	Ultraviolet
VOCs	Volatile organic compounds
1,4-DCB	1,4-Dichlorobenzene.

TABLE OF CONTENTS

ABSTRACT

The relentless ongoing pursuit of innovation, development, urbanization and immigration for a better quality of life has impacted the natural environment. Also, the various consequences of continuous industrial activities are seen in the departure from what is supposed to be the norms of nature and an ideal environment free of toxicity, pollution and unquantifiable instantaneous changes. One of these is variation in temperature experienced in recent times as against what it was about 2000 years ago before the industrial revolution. A world with an increasing population requires infrastructure to support this growth. The construction industry is able to support this growth by building necessary structures that will accommodate environmental sustainability. However, the construction industry is responsible for several environmental impacts as a result of various activities. Concrete is one of the major base materials used in the construction industry and cement is an essential ingredient in concrete production. Several environmental impacts ranging from high greenhouse gas (GHG) levels to high energy consumption (fossil fuel and electricity) to high resource usage are associated with cement production. Quantifying these impacts is a major roadmap to reducing them.

In this study an analysis of the production model of South African cement plants was carried out so as to quantify its impacts, and know how they consequently affect the lives of South Africans, her resources as well as the ecosystem; so that proper mitigation strategies can be recommended. The study carried out a Life cycle assessment (LCA) of cement using both the midpoint and endpoint approaches of the LCIA. LCA is a tool used to analyze the environmental impact of a process or product from start to finish. This study carried out a cradle-to-gate analysis of 1kg of cement produced in a typical South African plant using data from the Ecoinvent database and SimaPro 9.1.1 software. The result showed that for every 1kg of cement produced, O.993 CO_2 eq, was emitted into the atmosphere; 98.8% was actual CO_2 emission and its resultant effect was global warming which causes changes in climatic conditions. Also, 1.6kg of 1,4-Dichlorobenzene (1,4-DCB) eq was emitted into the air and water, which caused high toxicity in these media and for every 1kg of cement produced, 0.139kg of oil eq was produced and its effect was seen in fossil resources scarcity. Of this value, 0.125kg was from the burning of coal

In both approaches, the result was further analyzed with respect to five major production processes: (1) Clinker production (2) Raw material consumption (3) Electricity usage (4) Fuel consumption and (5) Transportation. The results showed that the clinker production stage contributed 76.3% to global warming; and raw material consumption contributed 95.9%, 99.9%, 90.7%, and 77.9% to ionization radiation, mineral scarcity, fossil resource scarcity and terrestrial ecotoxicity, respectively. Fuel consumption contributed 98.6%, 96.3%, 85.7% and 76.9% to freshwater eutrophication, marine eutrophication, human carcinogenic toxicity, and human non-carcinogenic toxicity, respectively. Electricity usage contributed 65.8% and 64.8% to stratospheric ozone depletion and fine particulate matter formation, respectively.

Though South Africa relies on the importation of clinker and cement, in the endpoint approach an estimation was carried out based on the annual requirement of cement in South Africa without importing either commodity. The result showed that 55 404 was the potential number of human lives that could be endangered annually; 133 species had the potential to be endangered annually, and the effect of a potential scarcity of resources caused total a marginal price increase of R6.2 billion due to these damages. The results of the analysis are in line with previously published literature but with slight variations. In conclusion, the study prescribed mitigation and adaptation strategies to counter these environmental impacts.

PUBLICATIONS

Published Articles:

B.D. Olagunju, O.A. Olanrewaju 2020. Comparison of life cycle assessment tools in cement production. Submitted to: South African Journal of Industrial Engineers (SAJIE) 2020.

Conference Papers/Abstracts Proceedings:

B.D. Olagunju, O.A. Olanrewaju 2020. Life Cycle Assessment of Ordinary Portland Cement (OPC) using the Problem-Oriented (Midpoint) Approach. Proceedings of 2nd African International Conference on Industrial Engineering and Operations Management, Harare, Zimbabwe, December 7-10, 2020. **(Published)**

B.D. Olagunju, O.A. Olanrewaju 2020. Comparative Analysis of Different Fly Ash Percentage of Pozzolanic Cement. Proceedings of the 5th NA International Conference on Industrial Engineering and Operations Management Detroit, Michigan, USA, August 10 - 14, 2020. **(Published)**

B.D. Olagunju, O.A. Olanrewaju 2021. Life Cycle Assessment of Ordinary Portland Cement (OPC) using the Damage Oriented Approach (Endpoint). Proceedings of 11th Annual Industrial Engineering and Operations Management Conference, Singapore, March 9-11, 2021**. (Published)**

Book chapter:

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CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter introduces the research and states the research problem and the aims and objectives of the research. The chapter also outlines the methodology, justifies and states the significance of the study, outlines its limitations, lists the research outputs, and outlines the structure of the report. This chapter also gives a brief history of cement and cement production in sub-Saharan Africa and globally, and discusses the present condition of the cement industry in sub-Saharan Africa.

1.1.1 Brief history of cement

The statement “building activities are as old as humans themselves” couldn’t have been truer. During the primal era, building construction was mainly mud huts and stone monoliths such as Stonehenge but the construction of Proto-cities ended pastoral life and ushered in society as we know it today. Construction has always been a major aspect of life, beginning with the construction of huts and shelters made by hand or by using simple tools and implements. A group of specialized craftsmen similar to carpenters and bricklayers began to emerge as buildings and cities became more substantial during the era of sculpture when slaves were often used for construction. Evolution and the continuous growth of the human population and the urbanization of society necessitated the increased development of formal shelters to accommodate this growth.

Urbanization and the growth in the population have led to an ever-increasing necessity for shelter. This has necessitated greater focus on the importance of effective building materials and practices. Around 2700-2500 BC, in the prehistoric Mesopotamia and Egypt, traditional construction was accelerated by the construction of the awe-inspiring pyramids, which were the first example of large permanent structures being built. Also, the Romans built complicated structures such as aqueducts, insulae, harbours, bridges, dams and roads throughout their empire and with this, construction evolved significantly as the population continued to grow [1].

Consequently, the construction industry all over the world took on a new perspective as new construction companies emerged and grew at a fast rate due to increasing demand. Presently, the construction sector is one of the most important sectors leading the way in industrialization [2].

The Nabataean traders, one of the several nomadic Bedouins, who dominated and operated a sequence of oases and established a small domain in the southern region of Syria and the Northern region, were the first to build concrete-like structures around 6500 BC. About 6000 years later they discovered the merits of hydraulic lime, which solidified under water. In producing this concrete-like substance the Nabataea discovered the need to keep the mixture as dry as possible by reducing the water content to a minimal level as excess water caused weakness and created holes in the concrete [3].

Figure 1.1: An ancient Nabataea building [3]

About 500 years later, they found a material that could waterproof their mixture just like the Romans, as they had a major deposit of fine silica sand within their reach. They discovered that when groundwater leaks into the silica sand, it forms a pozzolanic substance. When making their cement, the Nabataea took this deposit and mixed it with lime, and then baked it in the kiln they used for their pottery at the same temperature. In 1300 BC, the eastern constructors realized that by using a thin layer of damp burnt limestone to coat the outer layer of their pillars and walls made with clay, it reacted chemically with gases in the atmosphere to form a protective overlay. Although this was not the production of concrete, it was the beginning of cement manufacture [3].

The word ‘cement’ comes from the root word ‘caementum’, which means stone chippings like the ones used for Roman mortar and not the regular meaning of binding material. Hydraulic cement can be traced back to ancient Greece and Rome. This substance was formed by the slow reaction of water, lime and volcanic ash around 600 BC. By 200 BC, they integrated the use of concrete into all their constructions; they packed the mixture into wooden moulds and then stacked the solidified substance like bricks [4]. However, concrete technology experienced retrogression during the Middle Ages. In 476 AD, after the fall of the Roman Empire, the method of making this pozzolanic cement was lost until the recovery of the document that contained the description of this method in 1414.

This recovery regenerated interest in building with concrete. Concrete technology consequently improved greatly when John Smeaton discovered the novel technique of producing hydraulic cement from lime when rebuilding the Eddystone lighthouse situated off the coast of Cornwall in the south-western part of England (1756-1759) [3, 4]. He discovered that the mixture of pounded slag, clay and lime solidified under water and he therefore heated up the mixture of limestone and clay until it formed clinker, and thereafter he grinded it into powder [5, 6]. In 1824 a British bricklayer and builder named Joseph Aspdin finally invented Portland cement. He burned finely-ground limestone and clay until carbon dioxide (CO_2) evolved from the mixture and thereafter mixed it with water. He called it ‘Portland’ cement after the high-quality building stones mined from the Isle of Portland in Dorset, England [7].

Although this was a major invention and made significant progress in concrete technology, this cement was not produced at temperatures high enough to be the actual precursor of modern Portland cement even though history still regards him as its inventor. William Aspdin, his son, produced the first cement that contained alite (an impure form of tricalcium silicate). After a few years, Isaac Johnson produced the first batch of today’s Portland cement in 1845 by heating limestone and clay at much higher temperatures than those used by Joseph Aspdin around 1400-1500^{o}C. This resulted in calcination and mineral formation with high reactivity that displayed strong cementitious properties, and was similar to what is used today. Although fundamental materials were used to produce cement, what stood out was the production process: the use of ball mills for grinding, the use of a rotary kiln as opposed to a vertical shaft kiln and the addition of gypsum after clinkerization to improve setting time. This process of manufacturing Portland cement quickly, as seen in Figure 2, became prevalent in European countries and North America [6].

Rotary kilns have replaced vertical shaft kilns since around the 1900s. This has improved the technique and the environmental friendliness of cement production as the rotary kiln achieves an even temperature during clinker production, applies a radioactive mode of heat transfer, produces cement with increased strength, and is more efficient at high temperatures. Ball mills were used in the kiln for clinker production and gypsum was often added to the resulting mixture to improve the cement's quality [7]

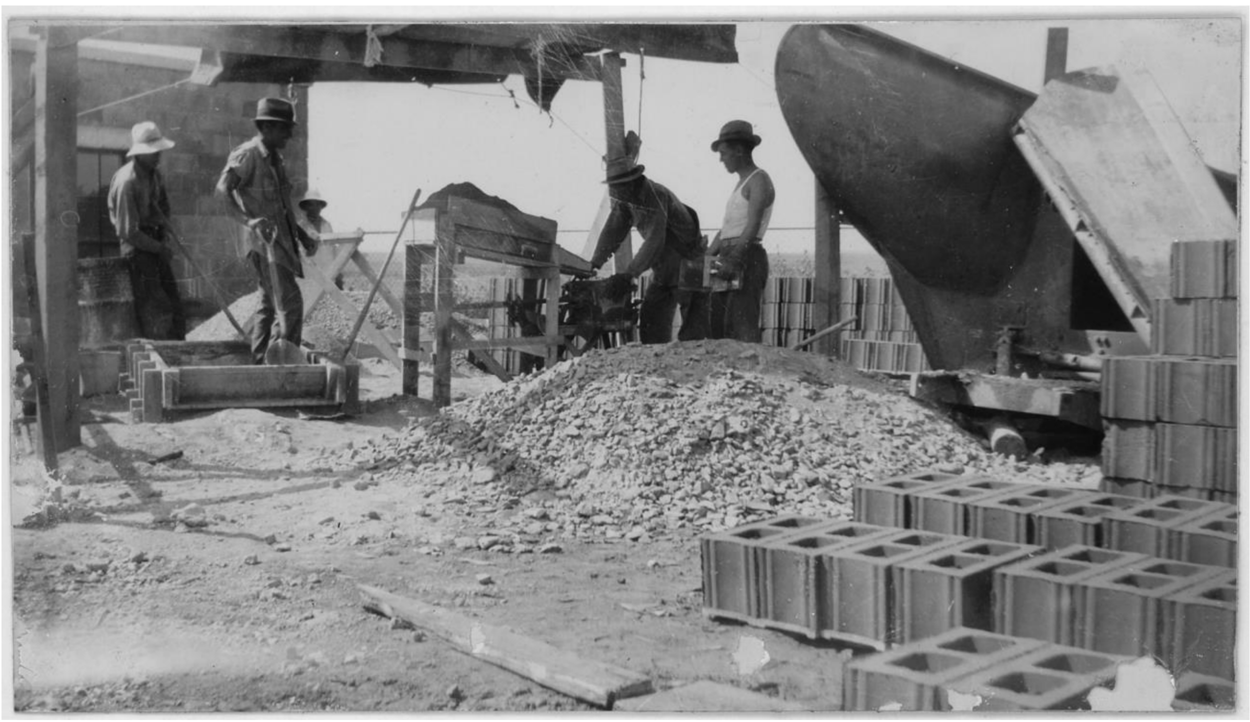


Figure 1.2: Mini concrete production plant [4]

In the 19th century, concrete was used mainly for large industrial buildings even though it was socially considered unacceptable as its appearance was not appealing. The emergence of the technological revolution in America at that time brought about the mass production of steel and this ushered in higher quality production processes and the use of Portland cement for houses, railroads, bridges and skyscrapers. The first well-known use of Portland cement was in England in 1850 and in France in 1880 when Frenchman Francois Coignet incorporated steel into the construction process [1, 4].

Air-entraining agents that greatly improved concrete's resistance to freezing and enhanced its workability were developed in 1930. This development was of great importance as it improved the durability of modern-day concrete by creating very small bubbles which were closely joined to each other and remained in the solidified concrete when these agents were added to the mixture. The chemical process of concrete solidification is known as hydration and this only takes place when the ratio of water to cement is 1:4. When there is water present in excess of this ratio, the concrete is easier to work with but as the concrete dries and solidifies, the water that evaporates leaves pores on the surface of the concrete into which water from the environment can enter and turn to ice in freezing temperatures which will cause water expansion. The consequence of this is cracks that are seen on the surface of the concrete, which will eventually grow larger as the process repeats itself and eventually result in surface flaking and deterioration known as spalling. However, if air has been entrained in the concrete, these small bubbles are compressed slightly and absorb some of the stress created by the expansion of water when it turns to ice. Also, entrained air improves workability and acts as a lubricant. Today Portland cement is made with both coarse and fine masses of stone, sand and water together with admixtures to improve the properties of the cement produced during both high and low temperature weather conditions [3]. Unprecedented concrete technologies and modernization are constantly being developed to enhance its sustainability and durability and the proper application of cement and concrete. While some innovative products integrate fibres and certain other aggregates to create roof tiles and countertops, cement which can absorb CO_2 over its span is also being produced, thereby reducing the carbon footprint of building material [7].

1.1.2 Cement in the sub-Saharan Africa (SSA) region

One of the most energy-intensive industries is the cement industry as the cost of energy is about 20-40% of the entire production cost. This energy is often more frequently utilized as fuel for the calcination process and as electricity for pulverizing the resources and even the cement itself. The energy consumed is about 4-5GJ/ton which amounts to 8-10EJ annually [8]. In 2004 there were about 75 cement plants in operation as seen in Table 1.1. Many of these plants were located in Zimbabwe, Tanzania, South Africa (SA), Senegal, Nigeria, Kenya and Ethiopia. Africa's market growth was about 9.4% in 2006, which gave producers space to increase their market share and expand their plant capacities. Also, the cement industry accounted for about 5-8% of the global anthropogenic CO_2 gas annually; while half of this CO_2 was from clinker production, the other half was from fossil fuel. It was therefore a major emitter of greenhouse gas and this made CO_2 mitigation important for this industry. According to a US Geological Survey (USGS) [9], data available from 2006 showed that cement plant capacity in SSA (excluding SA was 41.6Mtpa and had 45 MTs capacity in 2004 from about 75 plants in the continent including SA as shown in the Table1.1.

Table 1.1: Breakdown of cement plants and installed capacity in SSA [9]

	Number of plants	Production capacity of plant (tons)	Actual production (tons)	Capacity utilization
West Africa	29	19,241,000	8,779,130	46%
Central Africa	11	3,613,000	1,720,000	48%
East Africa	29	8,954,000	6,768,110	76%
Southern Africa	6	13,145,000	12,348,000	94%
Total	75	44,953,000	29,615,240	66%

West and East Africa had 29 cement plants each, showing that most of the cement workstations were situated in these regions. The central African region and southern African (majorly South Africa) region had 11 and 6 plants respectively. Many of the plants were in the following countries: South Africa, Kenya, Nigeria, Zimbabwe, Ethiopia, Ghana, Senegal and Tanzania. The cement industry had its thrust in Nigeria with about nine plant stations and a capacity of 9.75Mtpa, which was about 51% of the production capacity of West Africa. In East Africa, however, Kenya was taking the lead with about 2.75Mt capacity and Cameroon in the central African region was ahead with 1.2Mt production capacity in the year 2004. In 2004, the total amount of cement produced in Africa, excluding SA, was 17.3Mt and West Africa accounted for about 51% of this production followed by 39% in East Africa then Central Africa with 10%. The 51%, which was about 2.1MTs, from West Africa was majorly from Nigeria, Ghana and Senegal. Excluding SA, the capacity utilization in the rest of SSA cement was low (54%) as at 2004 when compared with that of India and SA, which was around 80-94%. Different regions varied in their consumption; while East Africa had a capacity utilization of about 76%, West Africa had 46% and Central Africa had 48%.

Nigeria's utilization capacity was as low as 22%. In East and Central Africa, the specific energy consumption of the plants varied from 105 to 140 kWh/ton and 800 to 1,000 kcal/kg of clinker for specific thermal energy and was distributed majorly in West Africa and East Africa, and accounted for about 46% and 42% respectively. In these regions, the major countries with the potential to cause high CO_2 emission were Tanzania, Nigeria, Ethiopia, Kenya and Senegal. Energy, being one of the most expensive inputs in the cement production process, could reduce the entire production cost of cement if it was used more efficiently. Particular attention should be paid to countries within the different regions with high production capacity to improve the efficiency and effectiveness of energy consumption in the plants. Such countries are Togo, Nigeria and Senegal in West Africa, and Tanzania, Kenya and Ethiopia in East Africa [10]. Increased consumption of cement in Africa has been primarily a function of four factors [11]: rising populations, rising infrastructure expenses, economic growth and increasing urbanization. The International Monetary Fund (IMF) forecasted the economic growth in SSA to be over 5% annually in the next six years from 2014 [12]. Generally, urbanization, acceleration of economic performance for sustainability and demographic growth have been some of the factors that have driven Africa's industrial, residential and commercial sectors as well as tourism and structural projects such as dams (for power), roads, railways etc. In certain countries, the infrastructure sector has equally been driven by post conflict reconstruction.

The cement industry in Africa is majorly operated by five top international companies, which are Lafarge (France), Holcim (Switzerland), CEMEX (Mexico), Heidelberg Cement (Germany) and Italcementi (Italy). However, the CEMEX and Italcementi plants are mostly situated in North Africa. The production capacity of the CEMEX plant in Egypt is 4.9 MTs per year whereas Italcementi has five plants with 12 MTs per year production capacity in Egypt and three plants and one grinding unit in Morocco with about 3.2 MTs capacity. Of the top five companies, only Heidelberg, Holcim and Lafarge have companies across a number of countries in the SSA regions with Lafarge being the largest of them all in the eastern and southern parts of Africa, while Heidelberg has its operations concentrated in West and Central Africa. However, these companies have had their ups and downs. In 2007 and into the early part of 2008, Heidelberg sold all its operating plants in Nigeria and Niger and also had plans to sell its plants in other SSA regions. As part of the restructuring of the cement industry in SSA, part of the Dangote group business in

Nigeria, Dangote cement, entered the cement market with only two cement plants and two terminals with total production capacity of 11 MTs annually (7mt from plants and 4mt from terminals). However, the order of things changed since Dangote cement of Nigeria entered the cement market in the 2000s. Dangote became the single largest producer with growth into 14 other countries on the continent and production capacity of 20.7 MTs as seen in Table 1.2. The post-merger Holcim-Lafarge became the largest producer on the continent with capacity of 22.5+ MT per annum [13]. These are two potential major rivals with a history of collusive conduct in the cement sector in African countries but other globally recommended organizations could weaken the competition. Holcim also implemented important restructuring by divesting significant operations in southern and East Africa to a new company known as AfriSam.

Table 1. 2: Sub-Saharan Africa's leading cement producers by 2013 capacity [14]

Company	Production capacity (MTs)	Countries of operation in SSA
Dangote cement	20.7	Nigeria, Benin, Cameroon, Senegal, Cote d'Ivoire, Sierra Leon, Liberia, Ghana, Congo-Brazzaville, Ethiopia, Kenya, Tanzania, Zambia, South Africa
Lafarge	19.5	Nigeria, Benin, Cameroon, Kenya, Tanzania, Zambia, South Africa, Uganda, Malawi, Mozambique, Botswana, Zimbabwe
PPC	18.0	South Africa, Zimbabwe, Botswana
Heigelberg	6.7	Sierra Leon, Liberia, Ghana, Tanzania, Benin, Gabon, Togo
Afrisam	5.8	South Africa, Lesotho, Botswana, Tanzania, Swaziland
ARM cement	5.5	Tanzania, South Africa, Kenya, Rwanda
Sococim	4.2	Senegal
Holcim	3.0	Nigeria, Cote d'Ivoire, Morocco, Tanzania, South Africa, Guinea
Derba Midroc Cement	2.5	Ethiopia
WACEM	2.0	Ghana, Togo

According to a global cement report in 2007, apart from China, the overall growth seen in the demand for cement in 2006 was about 5.8%. The report revealed important differences in the growth rate across different regions of the world. In the regions of Africa the growth was 9.4%, and was 3.5% and 1.4% in Europe and USA respectively whereas the Asian region had the highest growth of 13% in the North and growth was 22.4% on the Indian sub-continent [15]. In 2005, Kenyan consumption amounted to 1.57Mt as against 1.42Mt in the previous year. This increase was, in a way, as a result of the growth in the residential construction sector [16]. Within a space of one year (2006-2007), Lafarge posted a cement market increase of two MTs but International Finance Corporation (IFC) estimated 60.6Mt, which is still much lower than in Indian and China. Lafarge forecasted that consumption of cement in SSA countries might be more than double by the end of the decade (140 kg per capita) and that there was great potential for market expansion and growth of up to 6-8% annually. The increase in the demand for cement coupled with low production capacity has led to the importation of cement especially in countries with high demand. The rapidly increasing demand could not be met and when IFA recorded cement consumption of 60.6Mtpa, the production capacity was 56.3Mtpa. This was due to various factors such as shortages in some plants in Nigeria, low utilization capacity etc. that created a gap between production and demand for cement. In 2006 there was a demand for about 10Mt of cement from the market whereas only 3.7Mt was produced locally. About 65% of the market share was imported between 2001 and 2007. Countries like Tanzania, Nigeria, Ethiopia and Ghana were major importers during this period. Senegal, like SA, only began importing after 2004 while Kenya was also importing during this period. SA's importation of cement tripled between 2005 and 2006 [17]. The perception of long-term profit and significant potential for market increase have encouraged producers to invest in the modification of old plants and new production lines and expanding their existing capacity of production as a whole. Many projects were initiated by Lafarge under its strategic plan known as 'Excellence 2008' to increase cement produced in the SSA cement market so as to counter the strong international market growth. This company experienced an increase of 2.2Mt with 1Mt coming from SA, 0.75Mt from Zambia and 0.48Mt from Uganda. In the Central Africa and West Africa regions a project was launched to achieve an increase of 0.6Mt in its grinding plant in Cameroon and it was still considering a 4Mt increase project in Nigeria. The investment flow by other producers in the Nigerian cement industry was assisted by the activities of Dangote cement as Dangote cement benefited from an investment by the IFC with USD 75 million for the expansion of the capacity of its Obajana cement plant to about 4.4Mt per year [2]. Also, a USD 1.6 billion agreement with the Chinese firm Sinoma was signed to build six more production lines in Nigeria. Dangote planned to increase production capacity from 7Mt to 12Mt by 2010 [10]. The population of Africa as at July 2020 was 1.343 billion according to the estimate of the United

Nations with the SSA region contributing over 1 billion [18, 19]. The growth rate was about 2.6% and it was forecasted that the population of the sub-Saharan region would reach 1.1 billion by the end of 2020 and 1.25 billion by 2025. The distribution of the population throughout the entire region as at 2016 is shown in Figure 1.3. The growth rate in Africa, particularly in sub-Saharan Africa, was the highest in the world. The consumption of cement in sub-Saharan Africa in 2016 was about 109 MT (MT) while in the entire continent of Africa it was about 235MT. North Africa, with a population of about 17%, was responsible for about 54% of the total consumption. The growth rate of the sub-Saharan region at 5–10% annually has been stable for the past two decades. The time periods in which some countries had downtimes were utilized by other countries and growth was expected to continue at a stable rate as the population increased.

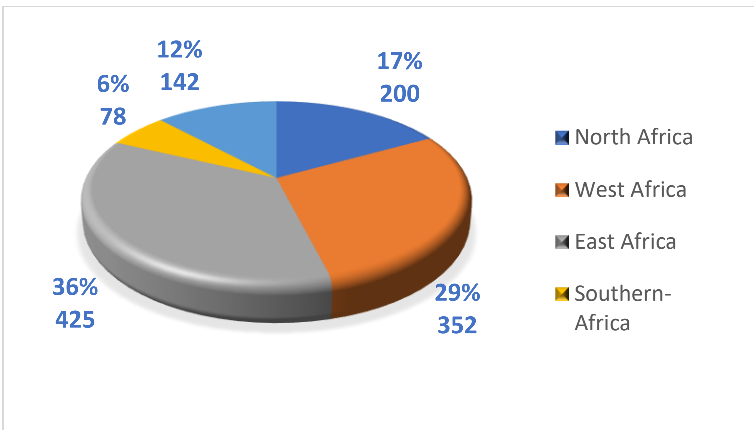


Figure 1.3: Breakdown of Africa's regional population in 2016 [20]

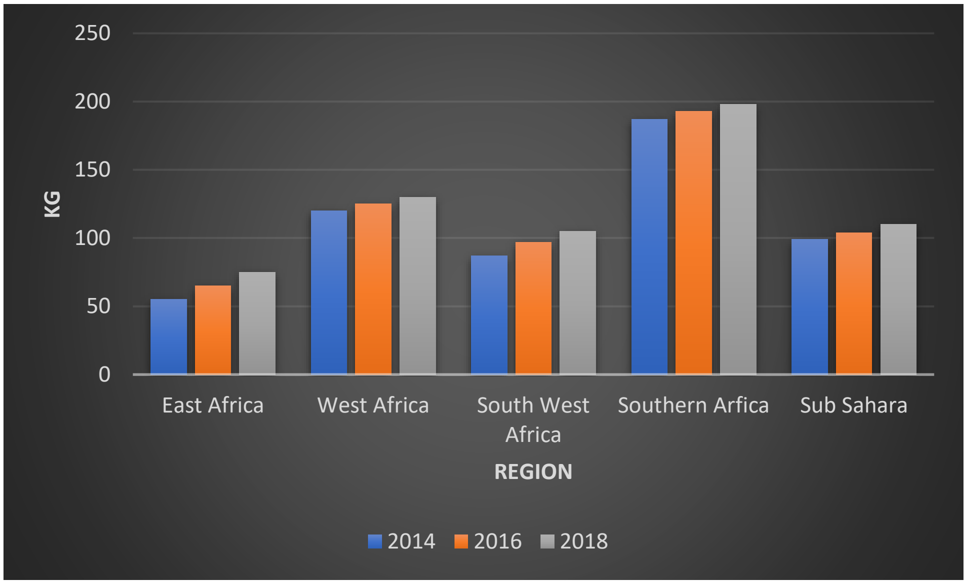


Figure 1.4: Cement consumption per capita in SSA [20]

Growth is expected to be continuous and maintain a 6% margin every year as it is assumed that other than SA, the SSA regions are still developing. In developing countries, cement consumption has often been 1-2% higher than the gross domestic product (GDP) as a result of essential investment in infrastructure. So as not to have a negative GDP increase per capita, an annual growth rate of 4-5% must be achievable; this is equivalent to a 3% population increase. In 2016 SSA cement consumption was 109 kg per capita whereas North Africa consumed 635 kg per capita. Figure 1.4 shows the development of regions in SSA since 2014. The large consumption of cement in southern Africa has been largely influenced by SA, which is a country with a more developed economy compared to other SSA countries.

Cement consumption per capita in South-West and East Africa together has been about half that of West Africa. Traditionally, the economy of West Africa has focused on industry and mining (oil and gas), and in East Africa the economy has relied on agriculture. Countries like Angola and the Republic of Congo in south-west Africa have abundant natural resources but political instability has significantly undermined economic development in these countries. Table 1.3 shows the forecasted future cement consumption assuming that the growth rate in the population will be 1.5-2% lower than the GDP growth as predicting the consumption of cement is a difficult task. Several factors ranging from the effects of global warming to a fluctuation in oil prices, political instability and outbreaks of pandemic among others could have a negative effect on such predictions.

Table 1.3: Cement consumption and production capacity [20]

SSA	2012	2014	2016	2018	2020
Cement consumption (thousand tons)	82,460	93,493	108,494	121,317	138,486
Growth rate (%)	8.63	10.06	9.94	5.93	6.34
Cement consumption per capita (kg)	92	99	109	116	126
Population (Million)	898	946	996	1,049	1100
Population growth (%)	2.52	2.17	2.54	2.55	2.43
Total clinker capacity (tons per year)	57,684	71,260	98,645	111,909	128,215
Total cement capacity (tons per year)	92,499	107,859	154,120	186,725	212,495
Total clinker cement surplus (tons per year)	10,093	14,366	45,626	65,408	74,009
Clinker surplus (tons per year)	-4161	1,140	17,275	20,922	24,350

However, a 5-6% annual growth rate on average is seen to be realistic bearing in mind all these factors and given that this is an outlier compared to the growth rate in any other part of the world. During the last decade the highest average growth rate has been seen in South-West Africa. Even though production is still low in nominal terms, the growth rate has been quite strong over the last few years. Figure 1.5 shows the estimated consumption of cement and the cement production capacity in sub-Saharan Africa from 2012 to 2020. It is difficult to find reliable statistics showing historical data, and even more difficult to make predictions for future years. To a large degree, sub-Saharan Africa traditionally imported cement and clinker to address its needs. During the last decades of the 20th Century, several cement mills were constructed; however, until the beginning of the 2000s, integrated production capacity was developed primarily in South Africa, Kenya, Tanzania, Senegal, Benin and Nigeria. Over the last 15 years, major investments have been made in cement production capacity and new clinker plants have been constructed wherever limestone was available [20]. The result is that there is now a large surplus in production capacity. Again, there are uncertainties related to the figures presented, regarding both the time of completion and the rated capacities. In addition, in many countries the realistic capacity to produce has been reduced due to a lack of electrical power, the unstable supply of kiln fuel for clinker production and for generators, and the periodic unavailability of transport. Despite the surplus capacity of 45 MT of cement and 17 MT of clinker in 2016, new investments in production plants have been announced almost on a weekly basis. Some of the projects may not be realized at all, or may be downscaled or delayed, while some new projects may be introduced. The surplus production capacity for both cement and clinker will likely increase, at least for the next 3−4 years.

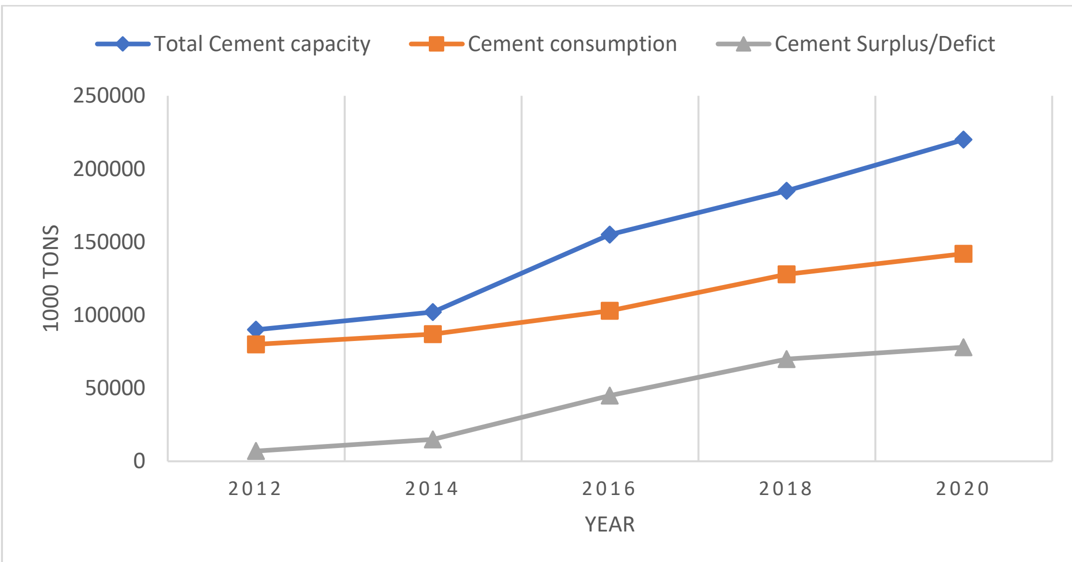


Figure 1.5: Sub-Saharan cement supply and demand [20]

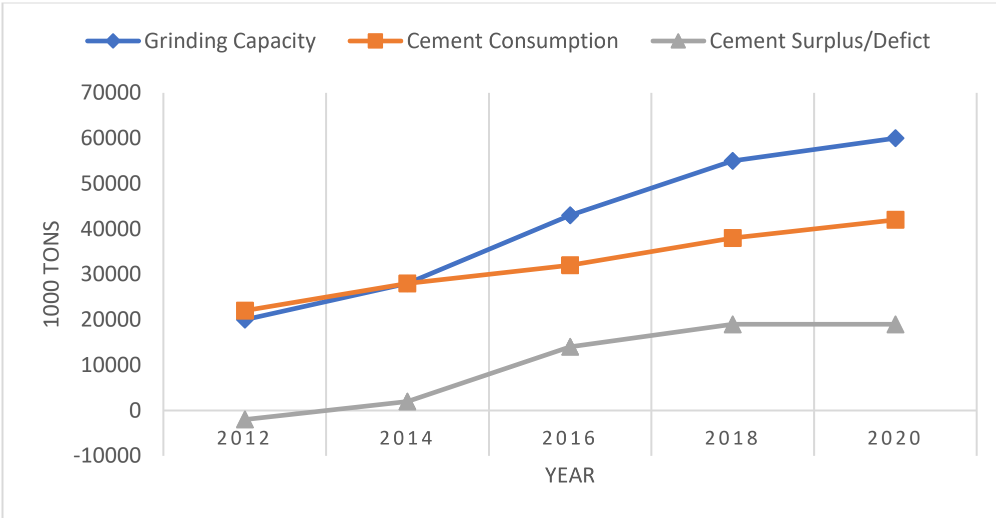


Figure 1.6: East African supply and demand [20]

1.1.2.1 East African supply and demand

As at 2013, East Africa's production fell short of demand but by 2016 this region had experienced a surplus of about 13Mt as illustrated in Figure 1.6. Major expansion projects were undertaken in every country in this region in 2010 but before then, development had been lagging. Although the region had experienced a supply surplus, some countries such as the Central African Republic, Malawi and Burundi still relied on importation to meet their demands while Mozambique had a capacity double the present demand. Some cement leakage was experienced in the eastern region of the DRC from Uganda and Tanzania and also in the southern part of the country from Zambia [20].

1.1.2.2 West African supply and demand

A major capacity development in West Africa was experienced around 2000 with the very first line of Ciments de Sahel in Senegal and Wacem/Diamond in Togo and Ghana. This region experienced self-sufficient production of both cement and clinker after a significant increase in the integrated capacity was installed in Nigeria. As presented in Figure 1.7, cement production was forecasted to be 40Mt more than the demand and clinker production 15Mt more than the demand. Ghana and Ivory Coast did not belong to this group (Nigeria and Senegal) that had surplus capacity and therefore relied on overseas importation to meet their demands. Mali and Niger, which are landlocked countries, will surely remain net importers while Burkina Faso will rely on clinker importation as it has a well-developed grinding capacity.

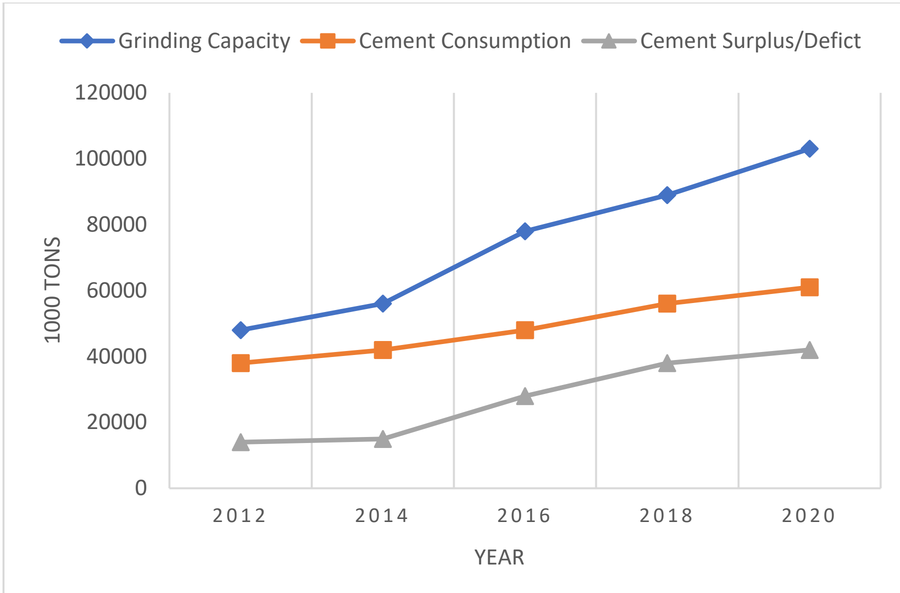


Figure 1.7: West African supply and demand [20]

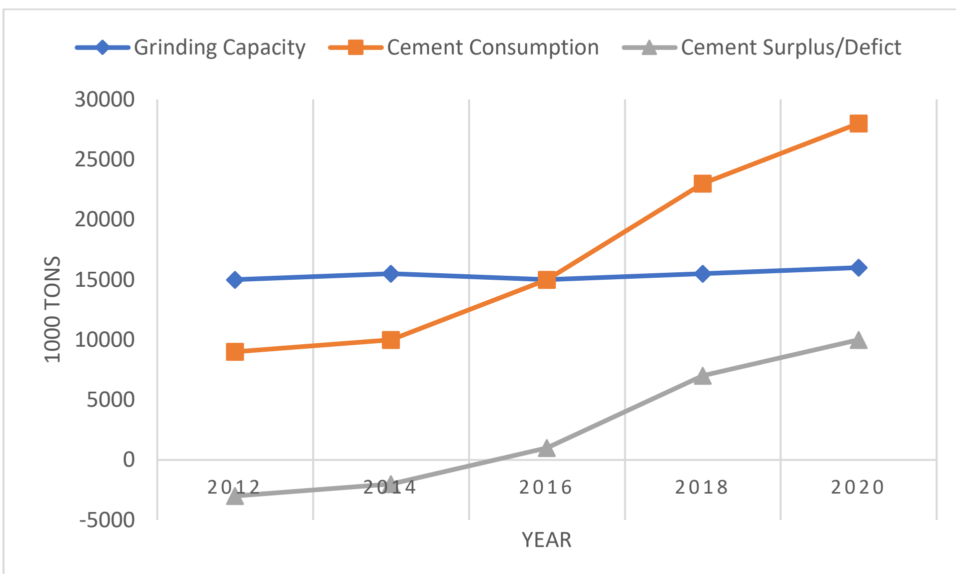


Figure 1. 8: South-west African supply and demand [20]

1.1.2.3 South-West African supply and demand

Investment in cement mills in Cameroon coupled with the installation of integrated plants in Namibia and Angola brought about cement capacity expansion in South-West Africa. In recent times, integrated plants have also been installed in the Republic of Congo and it is projected that major cement capacity will come to fruition in Cameroon in the coming years. LafargeHolcim, Medcem, Cimaf and Dangote had planned expansions expected to double 2016 capacity by 2020 as seen in Figure 1.8. Also, it was projected that integrated capacity would be installed in Democratic Republic of Congo and clinker would be imported from overseas for its grinding plants.

1.1.2.4 Southern Africa supply and demand

The demand for cement in southern Africa experienced an annual growth increase of 3% as seen in Figure 1.9. The increase in the cement production capacity in this region can be traced to the 3Mt production capacity of the Sephaku plant provided by Dangote. The new political dispensation in Zimbabwe was also seen as likely to lead to stronger growth in the demand for cement. The balance of supply and demand in SSA showed that there was significant excess in production capacity on this continent. However, the lag between supply and demand is set to rise in years to come. Ideally, when implementing a project, exportation is often part of the project plan; it is rather difficult to do this in SSA as importation is required in some countries that only have minimal market share and exporting overseas is not even realistic. Therefore, instead of leaving the production lines idle because of uncertain market alternatives, cement producers individually attempt to reduce the price to gain more market share. The implication is a large drop in the net sales price per ton. Significant differences can be seen in the price level from country to country as an average price drop of 30-40% has been experienced since 2012.

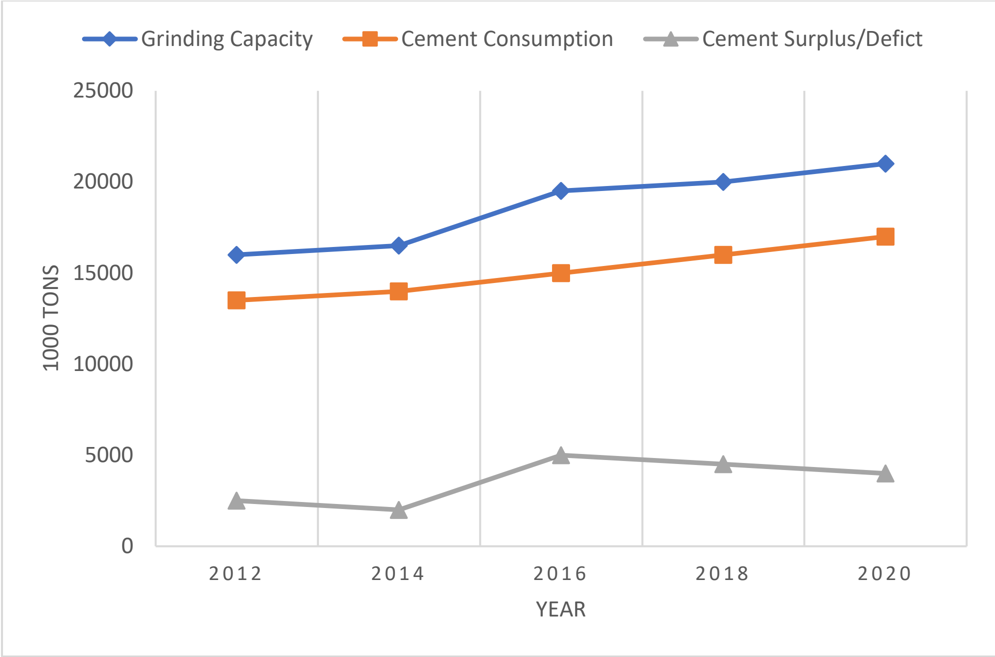


Figure 1.9: Southern African supply and demand [20]

The following international groups were known to be the major producers in the cement industry in SSA until the end of the 1990s.

- Heidelberg in West Africa and Tanzania
- Lafarge in East Africa, Nigeria, and Cameroon
- Holcim in West Africa, South Africa, and Tanzania
- Cimpor in Mozambique and South Africa.

The major cement producers have not really increased in terms of location except in Heidelberg through Italcementi as it is well established in North America. Since the late 1990s independent local producers and even new groups without previous investments in cement began to emerge. One of the first of these new groups was WACEM/Diamond which was acquired by the CIMAO clinker plant in Togo and started grinding processes in Togo and Ghana. This group now has a capacity of over 10Mt in over 10 countries. Ciments de Sahel is the second of these groups with a plant installed in Senegal in the early part of 2000. The total capacity of this group is over 4.8Mt with a new large integrated plant installed in Benin. Also, the Dangote group entered the cement trade in SSA in 2000 and commissioned the very first integrated plant in 2005. Dangote experienced exponential growth in the industry as a result of the newly installed lines and plants in Nigeria and now has different grinding terminals and integrated plants in all the regions of SSA. The sum total of the Dangote group's production capacity was 45Mt annually. In Morocco, Cimaf, a Moroccan Sefrioui Group member, which was affiliated to the construction/real estate development group Addoha, was also a recent entrant in the industry. Its first grinding operation was around 2012 and it experienced growth as it had facilities in about four countries in West Africa, Cameroon, and Gabon. This group still plans to intensify its capacity in West Africa by investing in Ghana and some other countries. Of all the local groups in southern Africa, PPC is by far the largest and most prevalent and is now expanding into other regions in an attempt to take over but it will rather focus on independent expansion. The SSA cement industry will in the future be characterized by excess capacity with low utilization capacity, a high level of competition and increased pressure on price. New plants are continually emerging and growing; however, different factors such as supply of fuel affect uninterrupted production. The demand for cement on the continent is growing faster than in any part of the world. Demand will eventually match supply in a few years from now [20].

The regional figures shown in Table 1.4, with the exception of South Africa, show that more focus should be placed on major cement producing countries such as Ethiopia, Kenya and Tanzania in East Africa, and Nigeria, Senegal and Togo in West Africa. In Central Africa, Angola is the only country that offers lucrative prospects. Apparently the capacity in South Africa is also somewhat significant (43% of SSA's theoretical potential) but these figures should be treated with the utmost caution [10]. The construction sector is one of the largest industrial sectors as it is one of the highest resource-intensive sectors. These resources range from natural raw materials to industrial energy which has considerable environmental impact. In 2018 the construction sector was responsible for about 39% of global CO_2 emissions and 36% of the global energy used as seen in Figure 1.10 [21, 22]. As at 2017, raw material consumed by this sector was about 90 Gigaton, which will continue to increase as long as the global population continues to grow [23].

Table 1.4: Breakdown of the Cement Industry estimation of different regions in SSA [24]

S/N	Countries	Number of cement plants	Installed capacities (tons/year)	Actual production (Tons/year)	Emissions reduction potential (tCO_2/year)	Initial investments (USD million)
WEST AFRICA		**13**	**14,210,000**	**7,610,600**	**975,718**	**148.6**
1	Benin	1	450,000	225,000	28,846	4.4
2	Guinea	1	360,000	165,600	21,231	3.2
3	Nigeria	8	9,300,000	3,700,000	474,359	72.2
4	Senegal	2	2,900,000	2,620,000	335,897	51.2
5	Togo	1	1,200,000	900,000	115,285	17.6
CENTRAL AFRICA		**5**	**3,140,000**	**1,969,000**	**252,435.9**	**34.4**
6	Angola	1	1,500,000	1,200,000	153,846	23.4
7	Cameroon	1	200,000	120,000	15,385	2.3
8	Congo - Brazzaville	1	450,000	100,000	12,821	2.0
9	DR Congo	2	720,000	360,000	46,154	7.0
10	Gabo	1	270,000	189,000	24,231	3.7
EAST AFRICA		**17**	**9,377,000**	**6,982,520**	**895,195**	**136.3**
11	Ethiopia	2	1,800,000	1,368,000	175,385	26.7
12	Kenya	3	2,650,000	2,200,000	282,051	43.0
13	Mozambique	2	760,000	577,600	74,051	11.3
14	Tanzania	3	1,700,000	1,292,000	165,641	25.2
15	Uganda	2	1,250,000	620,000	79,487	12.1
16	Zambia	2	51,000	392,920	50,374	7.7
17	Zimbabwe	3	700,000	532,000	68,205	10.4
SOUTH AFRICA		**10**	**13,145,000**	**12,356,300**	**1,584,141**	**214.3**
18	South Africa	10	13,145,000	12,256,300	1,584,141	241.3
	Total	45	39,872,000	28,918,420	3,707.490	564.7

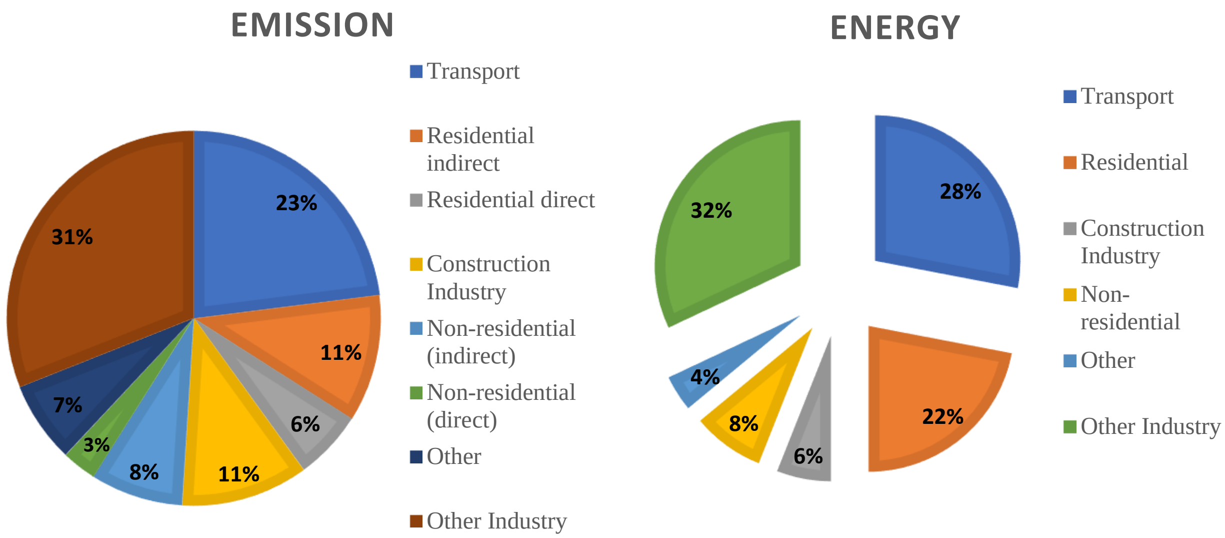


Figure 1.10: Global contribution of buildings and construction to energy and emissions, 2018 [22]

Continued production in the global cement industry is the result of global population growth. As the population increases there is a constant need to build infrastructure to accommodate growth t [25]. The cement industry is indispensable since cement is the major component required in the construction sector. However, the industry faces challenges that impact the environment. Global cement production reached 4.2 billion tons in 2019 [26] and it is projected to grow by 1.3-1.4%, amounting to 4.83 billion metric tons by 2030. It is important to understand the impact that cement can have on the environment as it is the main component used in the construction sector. Cement contributed about 8% of the world's CO_2 emission in 2018 [27] and 5% of this was emission from the production process excluding energy generation. The cement industry accounted for 12-15% of global industrial energy [28]. China had the highest population in the world and was therefore expected to be the highest cement producing country in the world. Its estimated production was 2.2 billion metric tons in 2019, with India following at 320 MT. China presently produces more than half of the world's cement and is thus the highest CO_2 emitter and energy consumer and significantly contributes to global resource depletion [29] as can be seen Figure 1.11.

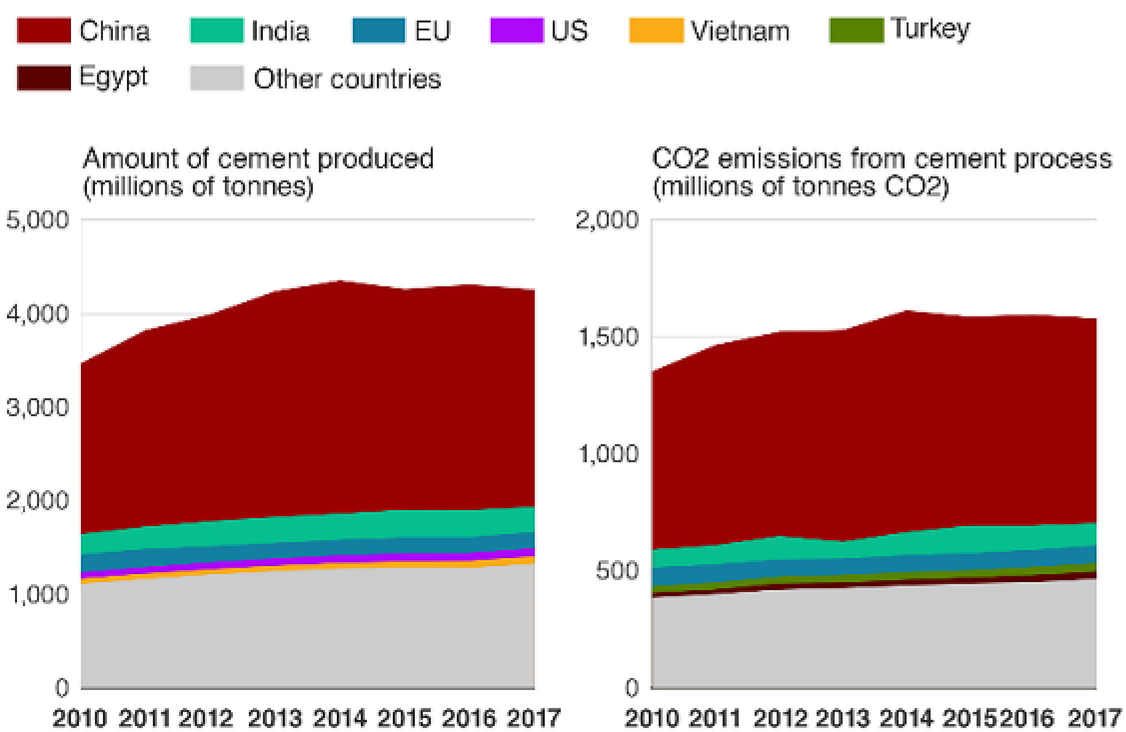


Figure 1.11: Cement production of populated countries and corresponding CO_2 emission [29]

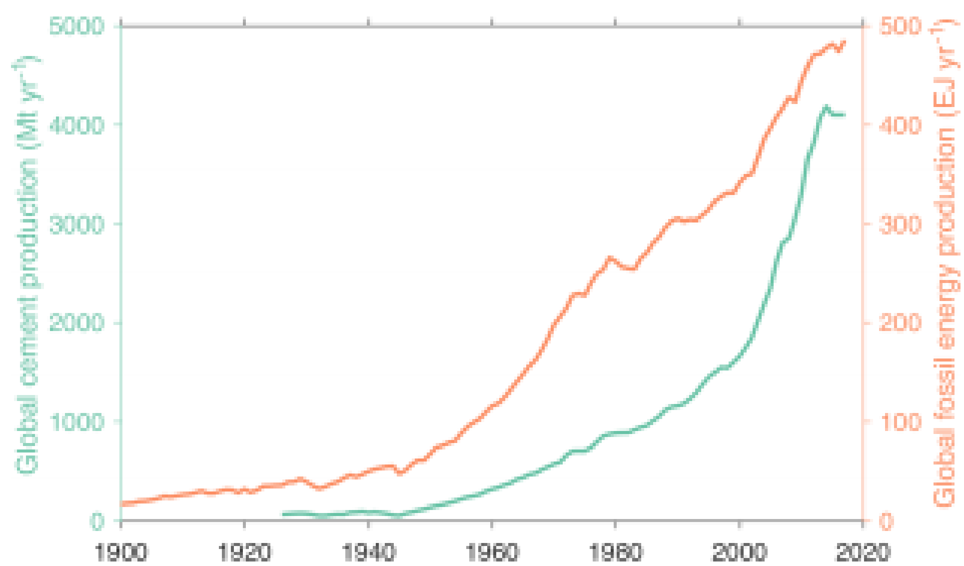


Figure 1.12: Global cement and fossil energy production to 2017 [30, 31]

Figure 1.12 shows a comparative analysis of the global production of cement and the fossil energy needed for the production. The major environmental impacts encountered in the cement industry are high CO_2 emission and high energy and resource consumption across the entire production cycle. Thus, there is a need to analyze the production process of this industry so as to optimize and improve its efficiency in terms of environmental impact.

1.2 Problem statement

Cement is of great importance as it is required for buildings and structures needed in a sustainable environment and consequently provides continuity of life. However, activities in the cement industry have various environmental consequences that affect not only human beings but other species as well. One of these consequences is global warming which brings about altered climatic conditions due to high Greenhouse gas (GHG) emissions in the atmosphere. Another environmental impact is high energy consumption during production as this can be a source of greenhouse gas and other pollutants which can increase production costs. It is important to conserve energy by improving the energy consumption in this industrial sector. Another prevalent impact of the cement industry is the high consumption of resources in the form of raw materials. With the high usage of resources in this industry, there will be a scarcity of raw materials if adequate precautions are not taken to preserve them.

1.3 Research Aim and Objectives

This research aimed to critically analyze the environmental impacts experienced as a result of every 1kg of cement produced and the effects of these impacts. The objectives of this study were:

- To identify the environmental impacts associated with the production process of cement.
- To affirm the environmental impact of cement production as stated in literature using the LCA that currently exists in the South African cement industry.
- To analyze the environmental impact of this process using both the problem-oriented approach (midpoint) and the damage-oriented approach (endpoint) of ReCiPe.
- To assess the effect of this impact on human beings, other species, resources and the environment as a whole.

1.4 Methodology

Life cycle assessment (LCA) is a methodology that analyses the production process of a product from start to finish using LCA software to evaluate the environmental impact of such a production process. This analysis is done by harnessing all input and output data (including emissions) needed to produce a product and running a simulation with it (data). The outcome of the analysis shows the different impact categories which can be traced back to the inventory where the impact hotspot can then be detected. The evaluation tool has four stages as prescribed by ISO 14040 [32, 33]. These are the goal and scope of study, the life cycle inventory (LCI), the life cycle impact assessment (LCIA) and the interpretation.

This study focused on the life cycle assessment of the entire production process of cement so as to calculate the impact of cement production on the environment. Production inventory data, which has to do with all input and output data required to produce cement right from extraction of raw materials to packaging, was collected and incorporated in the LCA software for simulation. The outcome of the simulation showed different production processes alongside the environmental impact they caused and also the substance(s) in the production process causing the environmental impact. Suitable recommendations were made thereafter. The data to be used in this study was collected from a South African cement plant.

1.5 Justification for the study

The environmental implications caused by the cement industry can be effectively accounted for when a LCA is carried out as the impacts span the entire production process. It is important to establish the root cause of these impacts as the problem can be tackled more effectively once the causes have been put into perspective. By doing so, meaningful recommendations on the best available technique (BAT) can be made. In addition, recommendation can be made on the replacement of resources that have a negative impact without affecting the overall output of the product: cement.

1.6 Significance of the study

This study aimed to carry out a life cycle assessment (LCA) study on cement production in a South African cement plant using both process-oriented and damage-oriented approaches. Based on the result of the analysis, this study has presented the particular production process that had the most environmental impacts, revealed the substance(s) causing this impact and made recommendations on how to mitigate these impacts. The impacts of this production plant on the environment were determined in the following damage categories:

- The damage to human life measured in DALY (disability-adjusted life years) based on the production requirement in SA
- The damage to the ecosystem in terms of species lost measured in species/year based on the production requirement in SA.
- The damage to resources based on the economic loss due to the price of resources measured in USD and based on the production requirement in SA.

1.7 Limitations

This study only covered the 'cradle-to-gate' assessment of the production process of cement; the data used from this analysis was from the extraction of raw material through to the production of cement. The packaging, use, disposal/end of life or waste treatment data were not taken into consideration in this study. Also, this study primarily analyzed the environmental impacts with large values that could cause pronounced damage. Impacts with minimal or negligible values were not analyzed. In addition, when using the two approaches, only characterization and damage categories were considered. Other tiers such as Normalization, Single score and Weighting were not considered in this study so as to reduce possible assumptions and uncertainties.

1.8 Structure of the research

The research focused on the LCA of the cement industry to evaluate the impact produced in its production. Therefore, the organization of the report will be as follows:

- Chapter 1 delivers the introduction and background to the dissertation.
- Chapter 2 presents a literature review of works already existing in this area.
- Chapter 3 focuses on the methodology used in achieving the objectives of this study.
- Chapter 4 analyzes the LCA evaluation using software by incorporating the data gathered and also discusses the results obtained.

- Chapter 5 is a conclusive summary together with recommendations for future work based on the study results.

1.9 Conclusion

This chapter has presented background information about the research area. It has given detailed information about the history of cement since inception to present date. In addition, the history, consumption, producers and production of cement in SSA have been well documented. The identified key areas were the problem statement, which has to do with the environmental impact of the cement industry, and the aim of the study, which was to analyze the environmental impact of 1kg of cement. Highlighted in this chapter were the objectives, the justification, the intended methodology and the research outputs that emanated from this study. This chapter also highlighted the structure of the dissertation and gave an overview of the study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter discusses the relevant literature deemed necessary to achieve the objectives of this study. This includes a brief description of cement and its production processes, and different applications of the Life Cycle Assessment (LCA) in the cement industry for different countries with the aim of mitigating Greenhouse gas (GHG) emissions and reducing energy/resource consumption. The chapter also includes a comparative analysis of different software tools. All published literature used in this review was obtained from knowledge-based sources such as ScienceDirect, Web of Science and Google Scholar to mention among others.

2.2 Cement

Cement is an essential material needed to build structures and buildings. It is primarily utilized in the production of concrete. Concrete is a combination of inactive mineral accumulates such as cement, gravel, crushed stone and sand. The production and consumption of cement have a close relationship with activities involved in construction and consequently in commercial activities. Cement is produced in almost all countries in the world due to the geographical abundance of its major raw material component and its importance in the construction sector. This prevalence of cement production is also due to the volume/density ratio, which, in turn, affects the cost of transportation together with the relatively low price of cement. The production of cement is extremely energy-intensive. In the late 90s, energy consumption in this industry constituted about 2-4% of the world's primary energy and about 5-8% of the world's total industrial energy [34]. In addition, the industry is a major emitter of CO_2 gas, which is the result of two major factors: clinker production (calcination) and carbon-intensive fuel sources. The calcination process is the chemical decomposition of limestone ($CaCO_3$) into quicklime (CaO) and carbon dioxide (CO_2) due to high carbon-concentrate fuel sources like coal, oil and gas etc. The emission from these sources coupled with the emission from electricity generation are the reasons why the industry is a major emitter of CO_2 and therefore requires assessment with the aim of reducing the carbon dioxide and energy consumption [35].

2.2.1 Cement properties

Cement is an inorganic, nonmetallic substance with hydraulic binding features. It forms hydrates when in contact with water and maintains its strength after solidification has taken place. By varying the source and quantity of additives and calcium various types of cement can be produced. Table 2.1 gives an overview of important cement types. The properties, or characteristics, of a particular cement type are a function of its composition though fineness is an essential feature for all cement types as it facilitates the setting rate and strengthens it.

Table 2.1: Summarized cement types (major), composition and raw materials required [35]

Cement type	Composition	Remarks
Portland[a]	95% clinker 5% gypsum	Gypsum improves workability of cement
Portland slag	60% clinker	
Portland pozzolana	40% slag, pozzolana, fly ash	
Portland fly ash		
Iron Portland (Germany)		
Blast furnace	20%–65% clinker 35%–80% blast furnace slag	Only granulated slag can be used, not air cooled
Pozzolanic	60% clinker 40% pozzolana	Important in countries with volcanic materials
Masonry	Mixture of clinker and ground limestone	Binder for brick work

[a]Named Portland because the artificial stone made from the first Portland cement (1824) resembled natural stone from the peninsula Portland.

2.2.2 Cement manufacturing process description

As mentioned above, the cement production process consumes a substantial amount of energy. As seen in Figure 2.1, there are three main production stages: the preparation of raw materials, the calcination process and the production of cement (the blending and mixing of clinker with additives). The entire process flow of cement production is as shown in Figure 2.2. Cement is relatively cheap; however, the density to volume ratio is high, and it is therefore recommended that the cement plant be situated close to both the raw materials and the end users (customers) to save transportation costs. The calcination process uses entirely fuel in an ideal plant while the other two stages make use of electricity. The kiln for clinker production in the calcination stage uses fuel for the production of clinker. This stage uses up about 70-80% of the plant's energy [34] which makes it the most energy-intensive stage, while finishing and raw material preparation are electricity-intensive.

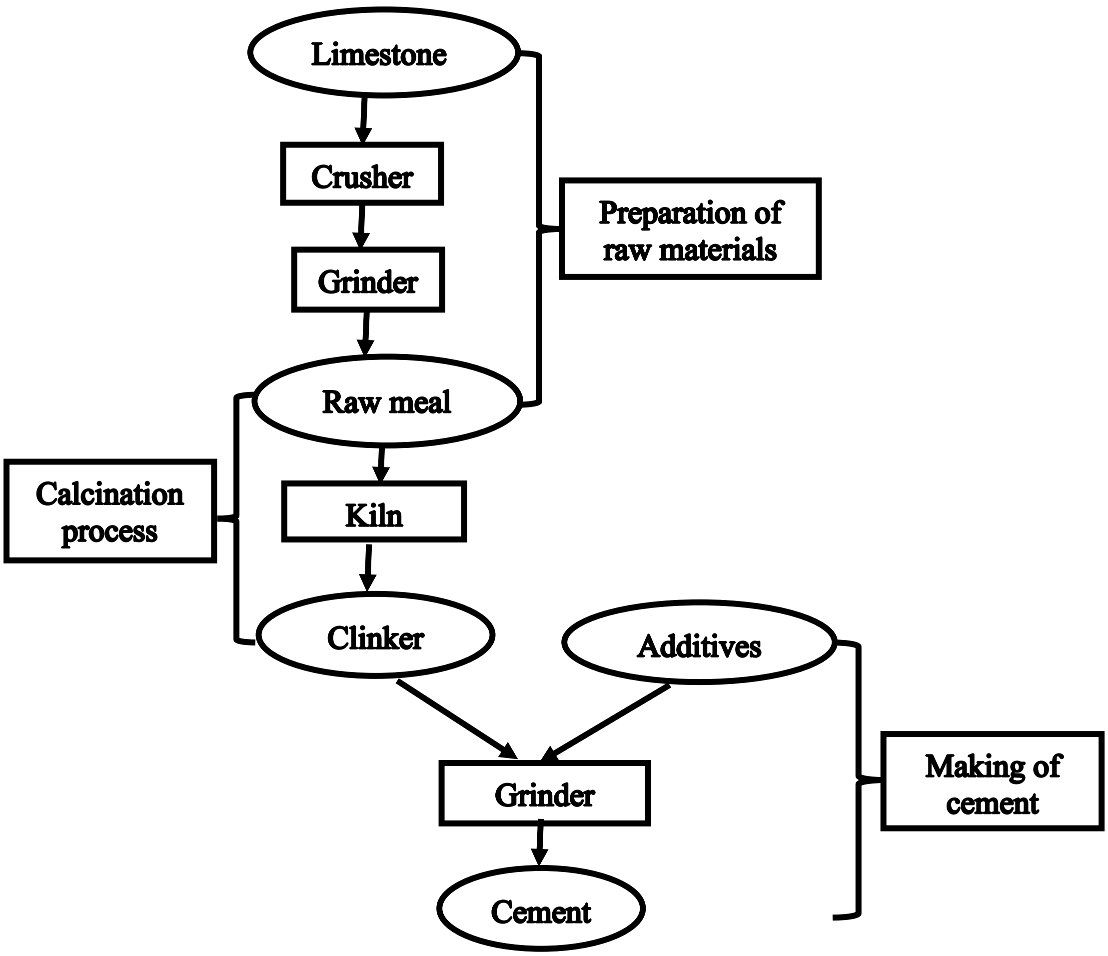


Figure 2.1: Modified schematic process of cement making [35]

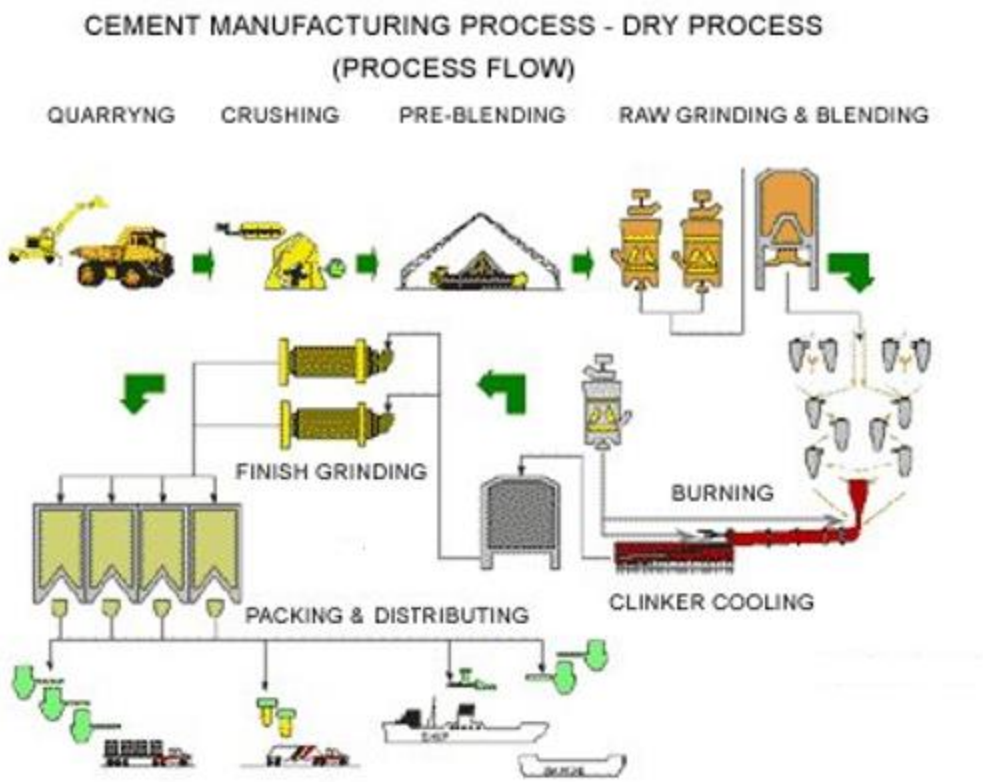


Figure 2.2: Cement manufacturing process: Dry process [36].

2.2.3 Raw material preparation

The most widely recognized materials used in the production of cement are clay, limestone and chalk even though a wide range of materials can be used [37]. Accurate and consistent raw material composition is vital for cement quality and uniformity. The choicest raw materials are extracted and combined. They are then crumbled and ground to a mixture with the desired chemical composition and fineness. This mixture is thereafter transferred for pyro-processing [37] [38]. A jaw, a gyratory smasher, a hammer mill or a roller can be used to crush the limestone. The mix is further processed and any stones remaining after crushing are removed. The mix is then ground using rolling mills or ball mills. The grinding process depends on the pyro-processing type that was used. The feed sent to the kiln is known as raw meal [39].

2.2.4 Clinker production (pyro-processing)

The mixture produced at the end of the pyro-processing is called clinker. About 1.65t-1.75t of raw meal is required to produce 1t of clinker. At a high temperature, the raw meal is burnt to first calcine the mix and then clinkerization takes place to produce clinker. Different kiln types are used in different places in the world. The vertical shaft kiln is mostly used in developing countries rather than the rotary kiln. Since the invention of Portland cement in 1824 by Aspedin, the vertical shaft kiln has been in use. However, the alternating operation of this kiln consumes high amounts of energy. In 1880 constant production of clinker commenced with the use of vertical shaft kilns. This was closely followed by the introduction of the dry rotary kiln. The wet process was later introduced to obtain a more uniform cement with improved quality to minimize dust and to achieve homogenization of the kiln feed and easy operation. By 1928 a semi-dry process known as Lepol was introduced. This reduced the amount of fuel consumed and also reduced the water content of the material that entered the kiln. In 1970 a pre-calciner system was introduced to further reduce energy consumption and boost productivity.

2.2.5 Cement making (finish grinding)

Roller mills, a roller press or ball mills can be used to grind clinker and additives together. The purpose of using additives such as gypsum, blast furnace slag, anhydrite and pozzolan is primarily to improve and control the cement's properties. The power consumed in grinding depends greatly on the type of additive used and the fineness of the end product required [40-43]. The setting time of cement and its other properties are influenced by the fineness of the cement.

2.2.6 Energy consumption in cement production

The hypothetical energy utilization for cement production can be determined in respect of the enthalpy of the formation of 1kg of Portland cement clinker, which is around 1.76 MJ [44]. In addition to the hypothetical minimum requirement of heat, energy is needed to dissipate water and to make up for the heat losses. Heat is lost by convection or radiation and also during clinkerization as dust is removed from the process. Energy consumption is, in practice, therefore, often higher. After the raw materials are crushed, ground and mixed together, the mixture is preheated and thereafter conveyed to the kiln for what is known as pyro-processing and the product of this process is what is known as clinker. This process makes use of fossil fuel for its operation and it is the most resource (fossil fuel) consuming process of all the production processes. The breakdown of energy consumption in the cement manufacturing process is as illustrated in Figure 2.3 [10]. The main energy intensive instrument in the entire production process is the kiln. Electricity is also consumed during the raw material preparation and cement finishing. However, the consumption of energy by the kiln depends on the wetness of the raw meal [38]. The power consumed by the rotary kiln is often about 17-23 kWh/t of cement clinker, which is relatively small although additional power is also consumed during cement packaging and by the conveyor belts. The total power used by the auxiliaries is estimated to be about 10kWh/t [45].

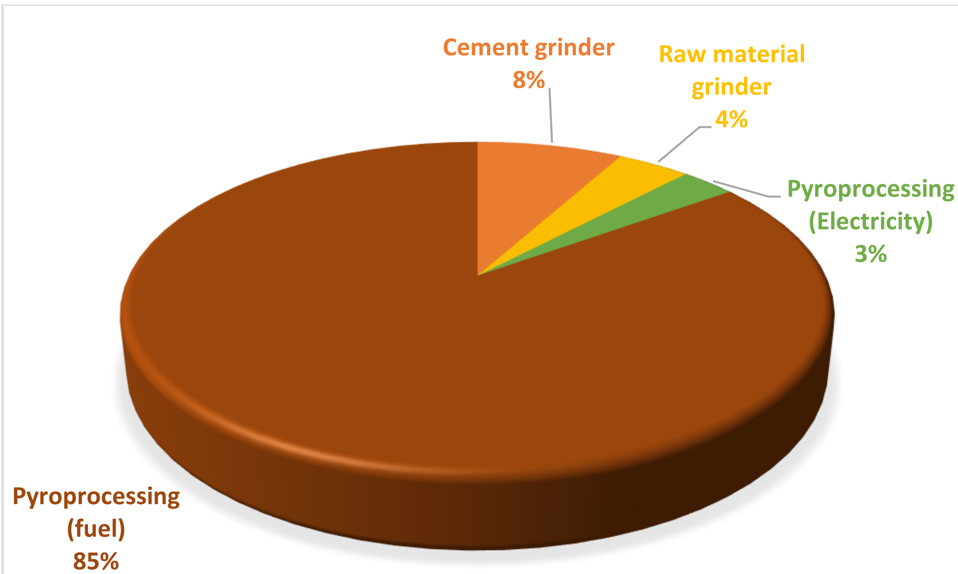


Figure 2.3: Energy consumption in the cement manufacturing process [10]

2.2.7 Carbon dioxide removal

The reduction of CO_2 can be achieved by the application of the CO_2 removal technique. This technique involves separating the CO_2 after the production process and thereafter either disposing of it or storing it. The CO_2 can be regained from flue gases that originate from the calcining and combustion processes. Conventionally, concentrations of CO_2 in the flue gas are often within the range of 14-33%. Combustion in a CO_2/O_2 atmospheric condition may be appropriate to regain the CO_2 due to the high quantity of CO_2 in flue gases emitted from the calcining. The CO_2/O_2 technique involves using oxygen for combustion as opposed to air. This requires removing the nitrogen from the air in the plant before the fuel oxidizes [46]. To control the temperature of the burner, the kiln would be fed with a mixture of CO_2 and oxygen [46].

The production capacity of cement has grown extremely fast in recent times, becoming the third largest cause of CO_2 emission after land-use change and fossil fuels. Getting accurate data to evaluate the emission in the cement production process is fraught and therefore relies heavily on assumptions. Also, the data used to evaluate global emissions has been perceived to be poor and highly inflated [47]. For the last 30 years several countries in the world have been producing cement types with varying clinker ratios, yet data with constant emission factors are still being used for global CO_2 emission estimation, which makes the database untenable. A study on global CO_2 emissions from cement production from 1928 to 2017 was carried out by Andrew (2018) with a large variety of databases available, including the latest estimations submitted by India and China and those submitted to the United Nations framework convention on climate change (UNFCCC), which were put together with priority being placed on emission factors from the official database with the aim of carrying out a new assessment of global emissions in a typical cement production process. This study was therefore able to show that in 2017 the global emission was 1.48 $GtCO_2$ ± 0:20 Gt CO_2, which is equivalent to approximately 4% emission from fossil fuels. From 1928 to 2017, the sum total of CO_2 emission was 36.9 Gt CO_2±2:3 Gt CO_2 of which about 70% of this value occurred in 1990. The study revealed that the 2016 global emission recorded in the global carbon project report was about 28% lower than the actual value [47, 48]. The new database for global cement presented by Andrew's (2018) study helped increase trust and confidence in an official database and also presented defendable datasets with minimal dependence on assumptions. This database was used for the very first time in the Global Carbon Budget 2018 edition with the intention of updating it every year with both methodological updates and data updates. As countries calculate their emissions to be recorded in the UNFCCC report, a good number of assumptions will be replaced by tenable data. However, more work is still required to be done particularly on the estimation of the processed emissions of India and China as they are the largest cement producers and consequently the biggest CO_2 emitters. Their emission estimations have significantly impacted the entire global estimation. Morsali (2016) made use of LCA methodology and SimaPro software to analyse the impact of the cement production process on the ecosystem, resources and human health. The results of the study revealed that in the production process of Portland cement, of all the impact categories, human health had the most pronounced value in terms of resource depletion and emission of substances into the air. The emissions into the air included sulphur oxides, methane, carbon dioxide, nitrogen oxides, zinc and nickel, while those released into water included arsenic, copper, cadmium, zinc ions, nickel and chromium [49].

In recent times the Republic of Korea has intensified its plans and searched for ways to reduce GHG emission. A good example was seen in the technological and implementation policy from the perception of the life cycle implemented in a building which included materials usage, waste disposal treatments, etc. Korea's Green Standard for Energy and Environmental Design is a certificate awarded for environmentally friendly buildings intended to save energy and reduce environmental pollution during their lifespan [50]. The demand for and implementation of the certificate has increased annually. Construction materials and building technology that reduce both the environmental impact and GHG are of great importance. It is now mandatory to prove the effect of reduced GHG of buildings. Cho & Chae in (2016) compared the life cycle carbon emission of particular buildings in South Korea built with conventional construction material with low-carbon buildings to analyze the reduction of carbon emissions. The evaluation was done using the life cycle assessment. The results revealed that low-carbon buildings showed about a 25% reduction in CO_2 emission per unit area when compared to buildings built with conventional construction materials. This showed that if more research on material technology for low-carbon construction materials were to be carried out and implemented, CO_2 emission would be greatly reduced. The life cycle CO_2 ($LCCO_2$) was carried out on buildings built with low-carbon concrete and energy-saving materials by using Korea's life cycle inventory (LCI) DB for construction materials. The following results were realized from the assessment:

(1) The effects of construction materials based on carbon reduction technology were: reduced number of resources consumed by incorporating recycled or by-product materials; reduced CO_2 emission by reducing the time period of the production process and/ or the use of alternative fuel; reduction in resource consumption through repair during the lifespan.

(2) Building with both traditional and low-carbon construction material is known as low carbon building. A summary of about 3115 tons of materials was added. Of all these additions, about 80% were from materials for building frames such as pipes, ready-mixed concrete, reinforcing bars, sand and gravel, etc.

(3) Based on the assessment of the carbon dioxide emission of input material, the major sources of this gas were found to be wood, ready-mixed concrete and reinforcing bars. In total, they produced about 92.7% of the CO_2 emitted every year,

(4) Throughout the 30 years of the construction of low-carbon emission buildings, the total carbon dioxide gas equivalent produced was 2,423,004 kg. At the manufacturing stage, construction stage, maintenance and operations stage, and the demolition stage, 20.1%, 0.5%, 78.0% and 1.4% of CO_2 were emitted respectively. When juxtaposed with valued opinions in literature and domestic studies that were simulated [51], the outcomes of this study were closely related with respect to the emission ratio of each stage: production phase (11.66%–15.85%), disposal phase (0.4%–0.61%), construction phase (1.49%–2.15%), and operation phase (81.39%–86.45%). In studies carried out abroad as well [52], the operation phase (77%–85%) was the highest, followed by the production and construction phases (14%–21%) with respect to the emission ratio. Thus, it can be concluded that the effects of carbon emission reduction and energy-saving will always increase during the building maintenance stage.

(5) With respect to $LCCO_2$ input material, heating energy and electricity were mostly used to manufacture ready-mixed concrete and had the highest carbon dioxide emission. This outcome is a function of the material input required for energy saving and low-carbon concrete [51].

2.3 Life Cycle Assessment of cement as applied in some countries

The cement industry in Brazil is regarded as being efficient in its energy consumption. Brazil makes extensive use of road transportation, which means that the distance between the plant and the fuel source needs to be taken into consideration as it will influence the resultant environmental impacts. The extraction of about 100kg of diesel oil can emit the equivalent of 62.7kg of carbon dioxide and promote fossil reduction by about 127kg of oil equivalent. A study on the assessment of the environmental impacts such as toxicity and resource reduction in a typical Brazilian cement plant was carried out by Stafford *et al.* (2016). LCA was used to assess a plant which produced two types of Portland cement in Brazil [53].

The intensity of the effects of resource depletion and toxicity impacts was influenced by the distance of the source from the plant. The result of the evaluation clearly showed that transportation had the highest contribution to the analyzed impacts while clinker and fossil fuel production was the second highest. In total these stages accounted for about 70% of carbon dioxide equivalent and 90% of trichlorofluoromethane, or Freon 11 (CFC-11) equivalent. The results clearly showed that the transportation step had the most impact, followed by fossil fuel production and clinkering. Together, these steps were responsible for more than 70% of CO_2 equivalent and 90% of CFC-11 equivalent. As seen in figures 2.4, 2.5 and 2.6, transportation has the greatest effect of all the analyzed impact categories. This is critical because most transportation in Brazil is via road and road transportation produces the highest environmental pollution. It is worth noting that the plant was outsourcing a percentage of the clinker used for production at the time the study was carried out. After transportation the other factors causing the most pollution would be clinker production and fossil fuels.

In 2014 a study aimed at providing precise information on the environmental impact in respect of greenhouse gas emissions and natural resource utilization in the South African concrete industry was carried out by Muigai, Alexander, & Moyo (2014). This was done by reviewing the existing practices in a typical South African construction field as well as the environmental implications and thereafter carrying out a cradle-to-gate assessment. Data on resource consumption, energy consumption and waste emission during mining as well as raw material processing in the space of four years (2005-2008) was used for the assessment. The carbon dioxide emission for every unit of material produced was extracted from the Energy Report produced for the Cement and Concrete Institute (C&CI) of South Africa. The results showed that an average of 39.7 MT of raw materials was used for concrete production annually and 32.1 MT of this 39.7 MT of raw materials were coarse and fine aggregates while the remaining 7.6 MT materials consisted of iron ore, clay, limestone and silica used to produce about 4.73 MT of binders (cement). With respect to the time period of data provided, it was realized that about 4.92 GT of CO_2 was emitted during the mining, transporting and processing of raw materials for concrete every year [54]. It was also observed that the cement production process was the major emitter of CO_2 emissions, contributing about 94.7% of the entire emissions caused by the South African concrete industry. An average of 45.4 MT of concrete was produced every year in South Africa between 2005 and 2008.

A study which incorporated an assessment of a grey cement plant in Italy was carried out by Moretti & Caro (2017). The study used the average amount of cement and clinker produced in

2014 from 11 plants in Italy. Using the LCA method, the mean values of 29 impact categories from different plants were weighed and calculated and the Ecoinvent 2.2 database incorporated into the SimaPro 8.0.5.13 software package [55] was used to evaluate the impact categories. The result of the assessment showed that of all the production stages, the main production process accounted for a high percentage of the total CO_2 emitted. Over 85% of the total CO_2 was from clinker production while over 79% was from the entire production process. The clinker production accounted for 62% and 43% of the total eutrophication potential and acidification while the entire production process accounted for 55% and 33%. Also, the main cement production process was responsible for 16kg/Milligram of biogenic CO_2 emission, 0.17kg/Milligram of recycling materials, 0.21kg/Milligram of residual component for use, and 116kWh/Milligram of the total electricity consumed needed as part of the production process. This result can be ascribed to the fact that over 95% of the energy source of a cement plant in Italy was from a non-renewable primary energy source. In addition, this stage accounted for 793kg/Milligram of global warming potential [56].

2.4 Application of best available technology (BAT) and alternative resources (AR) using the life cycle assessment

Alternative fuels (AFs) have several advantages for the cement industry. These include a reduction in greenhouse gas emission and minimal usage of non-renewable fossil fuels. Alternative fuels are created by replacing fossil fuels with materials that will be incinerated with minimal emissions, only leaving a residue. The process also minimizes energy usage. In a review on using LCA to describe the environmental impacts of cement production, the identification of alternative material that could be used in a quest to improve the impact of cement production processes and the clarification of methods and approaches when using LCA was carried out by Salas *et al*. (2016). The review showed that one of the most effective ways of improving energy efficiency in the cement production process was by using the dry production process and by applying the best available technique; this application was found to be both feasible and economical. Also, the use of alternative fuel, carbon capture and storage (CCS) and clinker replacement were seen as viable ways of reducing the environmental impacts of cement production [57]. Alternative fuel can be in the form of waste gases or heat. Materials that can be used for blended cement in the partial replacement of clinker are waste from palm oil, zeolite, recycled concrete, fly ash, etc. and a blast furnace can also be used. Of all the above-mentioned environmental impact mitigation methods, CCS is not entirely effective as it has a number of economic and technical limitations in its implementation. A comprehensive LCA of cement production at a Spanish plant was carried out by García-Gusano *et al.* (2015) with the aim of analyzing the effect of using monoethanolamine as an absorbent for post-combustion CO_2 capture technology. According to their analysis, in a completely optimized cement plant which applied BAT by using a 7:10 clinker to cement ratio and about 50% alternative fuel source, the effect of post-combustion CO_2 capture was a reduction in abiotic depletion potentials, ozone depletion and global warming of 11%, 27%, 15% respectively and the rest of the impact categories increased multiple times simultaneously [58].

Therefore, the result of the analysis showed that ozone depletion, global warming and the abiotic depletion potential impact category were improved upon while the land use potentials, eutrophication, ionizing radiation, acidification, particulate matter, photochemical ozone formation, human toxicities, ecotoxicity impact category increased with multiple effects with respect to the International Reference Life Cycle Data System (ILCD) 2011 and using the midpoint approach.

To ascertain the potential improvement that could be brought about in the cement industry in the USA and Europe, Boesch and Hellweg (2010) used the life cycle assessment methodology. They deduced in their study that by replacing fuel with thermal by up to 50%, together with the application of BAT, like García-Gusano *et al.* (2015) found in their study, Europe would experience a reduction of 9% and USA 18% in their greenhouse gas emission for every ton of cement produced; this would also reduce resource usage by recycling waste fuels/product. Also, the partial replacement of clinker with a mineral component such as fly ash or ground granulated blast furnace slag would be an effective way of reducing environmental impacts [59]. In addition, their work showed that using blended cement presented a lower environmental footprint than the conventional Portland cement. Therefore, the highest CO_2 emission reduction and resource consumption reduction could be accomplished by good blending rates in cement blending and clinker production.

A trend similar to the outcome of the application of BAT and AR could be seen in the study carried out by Boesch and Hellweg (2010), Salas et al (2013) and Holt and Berge (2018), thereby establishing a trend in the use of BAT and alternative resources; however, the effects varied depending on the alternative fuel or technology type used. Holt and Berge (2018) in their work used a life cycle assessment to analyze the cement production process using an alternative fuel, liquid hazardous waste, with the aim of improving the environmental impact of the system when compared to a facility using coal [60]. The result of their analysis showed that the environmental impact that had to do with freshwater ecotoxicity, global warming and acidification was reduced when coal was replaced with hazardous waste while the impacts associated with eutrophication and human toxicity (which can cause cancer) increased. Also, by cooling the exhaust gases, generating electricity and recovering heat wasted from the production process, the impact of utilizing grid electricity could be reduced and this would in turn reduce the overall environmental impact. The outcome of the analysis also affirmed that the co-burning of hazardous waste and the use of fossil fuel replacement such as coal during the production process of cement had reliable positive environmental consequences.

F. N. Stafford *et al.* (2016), in their work, evaluated the environmental impact of cement when waste was used as a partial substitute for fossil fuel in a cement plant in southern Europe. The alternative fuel employed in their study was scrap tyres and refuse derived fuel. This evaluation was done by carrying out a cradle-to-gate life cycle assessment using on-site primary data and secondary data from the Ecoinvent database. The result showed that processes with the highest impact contribution were fossil fuel consumption, electricity consumption of mills and atmospheric emission in the kiln [61]. The effect of atmospheric emission is mostly seen in global warming and other impacts except for abiotic depletion. This is as a result of the substantial emission of CO_2 gas. Also, the result of the evaluation revealed that high consumption of fossil fuels and raw materials affected abiotic depletion the most. Fossil fuel production was also found to be a significant contributor to eutrophication potential and acidification. Electricity consumption also contributed to acidification seeing that fossil fuels were used to generate it. The results are closely in line with studies carried out in several EU countries.

2.5 Comparative analysis of the environmental impact of the conventional production process of Portland cement and the incorporation of BAT (alternative fuel) into the production process.

Various modifications to the cement production processes produce different cement types; in other words, they are derivatives of traditional Portland cement due to alternative materials and technology used in the production processes. A project was carried out in collaboration with CEMEX, a global cement producing company and building material supplier, to add to the body of knowledge on improving CO_2 emissions for different cement production methods as well as different combinations of materials for cement production. The focus of the project was a cement company in Germany which consisted of a cluster of three plants known as Cluster West. Life Cycle Assessment (LCA) studies have proved that a combination of synergetic materials has advantageous consequences in respect of environmental damage.

Feiz *et al.* (2015) evaluated the global warming potential (GWP) of clinker production by comparing three different product combinations in both synergetic and linear production assemblies and also developed a simple LCA model for the cluster production with the aim of being able to compare different systems of production based on a few available parameters of information [62]. The study was successful and the result of the different product combinations was as follows: CEM I - Portland cement with about 92% clinker; the remaining percentage included additives. CEM III/A - blended cement with about 50% clinker; the remaining percentage included supplementary cementitious material: ground granulated blast furnace slag (GGBFS) such as byproducts and additives. CEM III/B - blended cement type with about 27% clinker; the remaining percentage included supplementary cementitious material: ground granulated blast furnace slag (GGBFS) such as byproducts and additives.

The assessment was carried out from cradle-to-gate with the CO_2 emission of Cluster West being the focus. The result revealed that CEM III/B with a high percentage of byproducts (GGBS) had the lowest emission of CO_2 while the highest was CEM I. The difference in their emissions was about 66%. A simple LCA model that used six key indicators as against about 50 parameters was also developed and could therefore be used effectively to model future changes in both products and plants. The study concluded that for the average product compared, Cluster West emitted about 45% less CO_2 than the emission recorded in 1997.

Huntzinger & Eatmon (2009) in their study made use of LCA to evaluate the environmental impacts of four different production processes of cement. These processes included the conventional Portland cement process and three other processes with alternative technologies which were blended cement (natural pozzolans), a cement production process in which 100% of waste CKD is recycled back into the kiln process, and the Portland cement production process in which CKD is used to seclude a part of the process associated with greenhouse gas emissions [63]. They carried out a cradle-to-gate assessment on these processes using the SimaPro 6.0 software package and inventory data from the software library as well as on-site data. The result revealed that cement blended with natural pozzolans (the second production process) presented the highest reduction of environmental damage closely followed by the use of CKD for seclusion (the fourth production process).

The recycling of the CKD process was found to be a little higher than the conventional cement production process in its environmental impact reduction. Although blended cement presents with superior environmental friendliness, its reduced CO_2 emission might be a delusion considering the current demand for concrete materials and particularly, cement. However, the use of CKD presents a way to reduce CO_2 emission and the entire environmental impact by about 5% over conventional Portland cement. The CKD recycling process also showed minimal environmental impact reduction compared with the Portland cement process. Noteworthy were the limitations of this study in terms of data collation, which gave rise to the use of more secondary data and may consequently have caused a variation in the result/impact values in a case of repeated studies.

Valderrama *et al.* (2011) carried out a study in Cementos Molins Industrial, a Spanish company located in Catalonia which has been producing Portland cement and calcium aluminate for over 75 years. The plant had in recent years experienced minimal environmental impact and improved quality and safety, to mention just two factors. This was as a result of an upgrade to its cement production plant. This was achieved through the concept of installing a new production line, L6, and integrating the best available technology technique (BAT) with respect to clinker production efficiency [64]. The new L6 line was used to replace the L3, L4 and L5 lines, which had been in operation for about 30 years. L6 assisted with the initial raw material treatment because it had two homogenization mills, a vertical mill with three rollers and a crusher, a silo with capacity of 16000 tons and a specific withdrawal control system to ensure the homogeneity of raw meal and kiln feed. The height of the preheating turret was about 120m with five cyclone stages, a selective non-catalytic reduction (SNCR) unit to reduce the NOx emission, and an in-line precalciner kiln [65, 66]. Therefore, this study presented an improvement in environmental impact as a result of incorporating BAT into the clinker manufacturing processes.

LCA was used to estimate and quantify the environmental impact; the SimaPro 7.2 software package was used to carry out the analysis and the two scenarios of cradle-to-gate life cycle assessment was evaluated to reduce any uncertainty. This was done by comparing the production line L6 with the former production lines. The result of the assessment showed that incorporating BAT in the cement industry resulted in an important environmental impact reduction in the production process of clinker. The most impressive improvement was seen in the energy efficiency of the new kiln, which consumed less fossil fuel with reduced emission: when 1kg of clinker was produced, the energy demand of L6 was reduced by 17% (3035MJ/t). It is known that the grinding process consumes the most electricity in the production process of cement, and BAT minimizes the high electrical energy consumed by incorporating equipment with minimal consumption of electricity. In the case of the L6 line, the roller mill for grinding raw material reduced the electrical energy consumed by 30% compared to the ball mills used previously. The reductions achieved by L6 with respect to the different impact categories were as follows: 5% global warming, 15% acidification, 17% eutrophication and 13% cumulative exergy demand. In addition, the reduction achieved by L6 in respect of the different damage categories was as follows: 11% for human health, 11% for ecosystem quality and 14% for resources.

García-Gusano *et al.* (2015) carried out a study focused on reducing the impact on the environment and human health of a Spanish cement plant by incorporating potential solutions provided by a European directive as well as best available technology (BAT) efficiency measures. The study carried out a technical analysis of the different stages of the production process of clinker by using LCA to analyze different scenarios in which BAT and substitution methods were integrated. This was done by using the 2011 International Reference Life Cycle Data System method recommended by the European Commission. In the clinker production stage, burning of fossil fuel had the most significant impact and the calcination process affected climatic changes. High consumption of electrical energy affects freshwater eutrophication (FE) and produces human toxicity which can cause cancer. The most important improvement seen was in the reduced energy consumption of the clinker kiln and the power consumed [58].

Seeing that the evaluation of alkali-activated cements and concretes (AACC) and concrete presented contradicting results, Plamondon and Habert (2015) carried out a comparative analysis of concrete and AACC using the Feret equation method which involved evaluating the regular volume of cement and water and also concrete strength. The resultant AACC mixes had a lower global warming potential (GWP) than other alternatives available for blended cements. Also, when other impacts were considered, the impacts of AACC were also reduced. The study therefore concluded that the future potential of AACC was in the production of bricks, using one part-geopolymer and hybrid cement [67].

Teh *et al.* (2017) measured the carbon footprint strength of cement and concrete production in Australia; this included ordinary Portland cement (OPC), geopolymer concrete production, standard ordinary Portland cement concrete and blended cement-based concrete. The aim was to compare the process-based and hybrid-based LCA methods using a case study of an Australian cement and concrete production plant [68]. The outcome of the hybrid life cycle assessment showed significant emissions of Greenhouse gas for OPC and the remaining types of concrete. This may have been due to an economy-wide system boundary (upstream process emissions) incorporated into the methodology. The result was a function of the method employed in allocating greenhouse gas emitted from slag and fly ash used for geopolymer concrete.

A comparative analysis of the environmental impact of five different concrete mixes: alkali activated fly ash natural aggregate concrete, natural aggregate concrete made entirely with river aggregate and a cement binder, recycled aggregate concrete with 35% substitution of cement with fly ash, natural aggregate concrete with 35% substitution of cement with fly ash, and recycled aggregate concrete with natural fine and recycled coarse aggregate (100% substitution ratio) and a cement binder with equal workability and strength was carried out by Marinković *et al.* (2013). The analysis showed that the high-volume fly ash recycled aggregate concrete mix and the alkali activated fly ash concrete mix with natural aggregates had the most improved environmental performance, while the recycled aggregate concrete mix with a cement binder performed poorly.

This outcome was in line with the study carried out by Ouellet-Plamondo and Habert (2015) in that minimal emission was recorded and consequently environmental impact was reduced by presenting lower GWP.

Georgiopoulou & Lyberatos (2018) carried out a LCA study of cement when alternative fuels were used so as to compare the environmental impact of using alternative fuels with conventional fuels in kiln operation. Seven scenarios were established for the production of one ton of clinker in a rotary kiln. Each scenario contained each of the three alternative fuels or their mixture (partial replacement with coal or peat coke): BS (biological sludge), TDF (tyre derived fuel) and RDF (refuse derived fuel). A worksheet model was established and utilized for the estimation of the designed database from the operation stage of all the alternative scenarios. The results revealed that the most environmentally friendly scenario was the one based on RDF, while the next preferable scenario was the one based on BS [69].

This result resonated with a study conducted by Çankaya & Pekey (2019) on the comparative analysis of both the alternative scenario (AS) and traditional scenario (TS) of the cement production process in a typical Turkish plant with respect to the principles and guidelines stated by the International Organization Standardization (ISO) for using the life cycle assessment methodology [70]. The AS involved using alternative resources, which included fuel (alternative fuels were RDF, residual oil and dried sludge), while the TS involved the conventional resources. The analysis was carried out on a ton of clinker and cement using SimaPro 8.0.4 software and IMPACT 2002+ life cycle impact assessment method. AS was at all times better for non-carcinogens and the entire environmental implication gave a better outcome at 62% iterations when compared with TS. Substituting 3% of alternative resources with traditional resources resulted in a saving of 12 kg CO_2-eq/clinker. The outcome of the evaluation for clinker production revealed that the entire environmental implication was reduced by about 12% when AS was used. The damage assessment showed that the effect on the ecosystem, climatic conditions, resources and human health was reduced by 10%, 1.4%, 11% and 27% respectively. Overall, the AS had about a 3% positive improvement on the environmental consequences of clinker production. Also, the different types were considered and the CEM IV and CEM II were found to have minimal impact due to the use of trass. The greatest reduction of total environmental impact was seen in CEM IV (20%). The result of the assessment also showed that global warming potential was not greatly reduced by replacing fossil fuel with alternative fuels for different types of cement and clinker except for CEM IV. In addition, the result affirmed the significance of alternative technology: waste heat recovery technology and the clinker to cement ratio on the environmental impact of cement manufacturing.

We see in all of the studies, just as Salas *et al.*[57] predicted in their review, that the best way of achieving efficiency and effectiveness in the cement industry as well as achieving good environmental performance with minimal environmental impact was to incorporate BAT, and an alternative resource (fuel and clinker replacement) not limited to: BS, slag, fly ash, CKD, palm oil, TDF, blast furnace, wastes, zeolite, RDF, recycled concrete, and GGBFS. An abundance of results has been achieved in all these studies because the LCA assessment was used by individuals or corporate bodies to assess the cement industries of various countries or private companies. Few if any studies have been recorded in respect of the life cycle assessment of the cement industry in South Africa even though it is the biggest cement producing country in Africa; therefore, there was a need for this study.

2.6 Requirements of LCA software tools

The assessment of environmental impact is a complex process [71]. Therefore, there is a wide variety of software tools available to effectively carry out this assessment with one variation or another but not without some similarities although they can vary in their elemental features such as database, methodologies applied etc. Ormazabal, Jaca & Puga-Leal in their study in 2014 stated that when environmental impact is being assessed, some critical parameters required by the software tools are: user-friendliness, volume, quality, accuracy and relevance of data available [71]. The following are the features required for a reliable software tool.

2.6.1 Database

The information in the database needs to be transparent and of high quality (that is, include characteristics of data that relate to their ability to satisfy stated requirements). A high-quality database is one that contains not only the source and age of the data but also its composition in terms of where the data was generated from, the different contributions of literature and the number of companies that contributed to its documentation. Also, data should be able to update automatically as often as possible and possibly be connected to an internet homepage. Data should be stored and managed in a clearly structured database or library different from the modelling interface. A very convenient database for most users is one similar to MS office (a system that can be easily related to) where data can be modified without interfering with the major workspace. Also, a good software product should have a sensitivity analysis.

2.6.2 User-friendliness

Of fundamental importance is a self-explanatory and well-structured user interface. A user should feel comfortable working with the software due to its flexibility. It should require minimal time to gain mastery of the tool. It should also be simple and concise in its results presentation, showing the best options. Different versions and a free demo version showing a quick overview of the functionality and features of the software should be available in a software tool. Software ergonomics is of great importance in software design as this would allow continuous improvement and the elimination of malfunction, and increase the user friendliness index. An Internet homepage with detailed information should be provided for an LCA software tool. Information for beginners as well as experts should be readily available and an internet homepage with all the necessary information should be available. Other features that will allow the user to assess results easily and allow for further evaluation are of great importance. Most often in linear equation systems, definition of the quantity of input and output would also be sufficient, although scripts might be essential for some processes.

2.6.3 Structure

An essential component of high-quality software is a hierarchical structure in order to ensure transparency and modelling comfort. Results should be traceable in the calculation module for the user to be able to trace mistakes easily. The reports from the modelling should be linear and analytical. A process chain that uses graphical modelling is convenient and user friendly. The software should contain all the necessary features such as the assumptions and methodological solutions (assessment methods). Also, the user should be able to model different outputs, get lucid results, have a choice of starting points, and the compatibility of the software with other applications should be assured.

2.6.4 Uncertainty analysis

This is a prevalent analytical technique in a life cycle assessment tool. It primarily refers to the uncertainty of measured parameters (for example, inaccuracy of emissions measured or of normalization data) and the variability between sources (for example, various emissions of similar processes) and objects [72]. A simple parameter variation through statistical modelling methods such as the Monte Carlo simulation would cater for these potential distortions. These procedures are suitable for evaluating the effects of the uncertain parameter in the model output and consequently, the accuracy of the overall model. Thus, a good LCA tool is one that incorporates uncertainty and variability analyses.

2.6.5 Impact assessment methods

The definition of LCA comes from the application of a set of documented characteristic features that complies with the recommendation of ISO 14040 standards. The two prevalent and internationally recognized methods for LCA are the CML 2001 method [73] and Eco 99 [74]. They are a guide to the operation of ISO standards and follow different approaches: CML is a problem-oriented method and Eco 99 indicator is a damage-oriented method. When CML is used in isolation, the software will still require another means to interpret the result. In recent times, ReCiPe was developed to harmonize these two approaches, while the midpoint is the problem or process-oriented approach and the endpoint is the damage-oriented approach. Thus, a good software tool should provide at least these two methods. Also, a good impact assessment method should be able to choose among the different methods available, choose the result collection style and compare scenarios with various outputs.

2.6.6 Presentation

The user will, as a matter of necessity, present the results to different groups of people. Therefore, a good software tool should have a presentation outlook. A good process chain can be well represented using a Sankey diagram. A Sankey diagram is a specific type of flow diagram that shows all the primary energy flows in a system. It is a pictorial representation in which the width of the arrows is linearly proportional to the flow rate. Visualization of the energy report, the material flow both at regional or national level, and cost breakdowns are included in its operation. The Sankey diagram highlights the major flows in a system and helps locate the significant contributions to a flow. Also, the results should be presented in a structured hierarchy and allow the creation of diagrams. The hardware requirements should also be adequate.

In general, the main reason for using LCA is to calculate the environmental influence, the environmental hot spots (processes and substances that produce great environmental impacts) and the potential impact associated with a product and use the results in decision making. In evaluating the life cycles of products, the output is often the major focus. The major question is then: How can a quantity of cement produced yield minimum environmental impact? A good software tool should be able to answer this question. Ormazabal and Young [71] in their work opined that the most suitable software options for LCA in the cement world are those that have the following characteristics:

- Availability of a quality database
- Compliance with ISO 14040 series for LCA standards
- Can be used to achieve a full life cycle assessment methodology from goal and definition to LCI to LCIA to interpretation [71, 75].

2.7 Comparative analysis of life cycle assessment tools in cement production

There exist over 45 LCA software tools in the market and some are more suitable for cement production than others. A study was carried out to assess the accessibility and importance of these tools and also to streamline direction to the suggested useful ones. The absence of some specific tools that are not present in the list should not be considered as an undesirable recommendation. The study considered different sources which included a website of software producers, literature, software reviews and LCA resources. However, these tools present a wide range of skills and these skills are suitable for specific audiences which could be LCA practitioners, product designers, environmental managers, process engineers etc., and also for the type of LCA performed, be it full LCA or quick LCA. The major difference between the two is the quantity of the database required [73, 76, 77]. Table 2.2 below shows a list of all the tools that were considered in this study.

Table 2.2: List of software tools

S/N	Name	Vendor/ Developer	Tool	Database	ISO 14040 Guidelines	(DQA)	LCIA	Statistical analysis	Comments
1	AIST-LCA v4	National Institute of advanced industrial science and technology (AIST), Japan.	Y	Y	Y	N	N	N	www.aistriss.jp/main General
2	Athena	Athena Sustainable Materials Institute Canada	Y	N	N	N	Y	N	www.athenasmi.org. More focused on building & construction
3	BEES 4.0	National Institute of Standards and Technology, USA Technology,	Y	Y	N	N	Y	N	www.nist.gov/el/economics/BEESSoftware.cfm More focused on building & construction.
4	Boustead	Boustead Consulting, UK	Y	Y	Y	N	N	N	www.boustead-consulting.co.uk Reduced relevance, standard LCIA Parameters

5	Build-it	IKP, University of Stuttgart	Y	Y	N	N	Y	N	
6	CMLCA	Leiden University, Institute of Environmental Sciences (CML), Holland	Y	Y	Y	N	Y	N	www.cml.leiden.edu/ software/
7	Design system 4.0	Assess Eco strategy Scandinavia AB, Goteborg, Sweden.	Y	N	N	N	Y	N	http://www.ecosmes.net/cm/viewDoc?id=6564&l=EN General but limited
8	E^3 DATA BASE	Ludwig-Bölkow- System Technik GmbH, Germany	Y	Y	N	N	N	N	www.e3database.com
9	EARTHSTHER TURBO	GreenDelta GmbH	Y	Y	N	N	N	N	www.greendelta.com
10	ECO-BAT v4.0	Haute Ecole d'Ingénierie et de Gestion du Canton de Vaud, Switzerland	Y	N	N	N	Y	N	www.eco-bat.ch
12	Ecolab	Nordic Port AB, Sweden	Y	Y	N	N	Y	N	www.ecolab.com

13	EcoMa nager	Franklin Associates, USA	Y	Y	N	N	N	N	https://www.ka ercher.com/ca/s ervices/professi onal- LCI Tool, US/U K data
14	Eco Assesso r	PIRA, UK	Y	N	N	N	Y	N	Only literature data
15	Eco-Quantu m	Netherlands	Y	N	N	N	N	N	www.ivam.uva. nl/?id=2&L=1 Specific for building
16	EcoSca n 3.0	TNO Industrial Technology, Eindhoven, Netherlands.	Y	N	N	N	Y	N	www.ecosmes.n et/cm/viewDoc? id=6564&l=en General but limited
17	EDIP LCV Tool	Institute for Product Dev elopment., Denmark	Y	Y	Y	Y	Y	Y	http://lca.jrc.ec. europ a.eu General but limited
18	ELCD	EU	N	Y	N	N	N	N	Http://lca.jrc.ec. europa.eu General but limited
19	ENVES T	BRE, United Kingdom Sponsored by UK Department of Energy, Transport & Regions	Y	N	N	N	N	N	http://envest2.br e.co.uk/ Used with BRE environmental profiles databas e listed below Uses Eco-Points based on equiva lencies to comp

									are building design options. Specifi c for building
20	EQUE R	FRANCE	Y	Y	N	N	Y	N	Specific for building www.izuba.fr/lo giciel/equer
21	Gabi	IKP Uni. Stuttgart/PE Germany	Y	Y	Y	Y	Y		General but ver y suitable for building and assemblies construction www.gabi-software.com/
22	GEMIS	Oeko Institu te, Germany	Y	Y	N	Y	N	N	www.gemis.de emission model ing software General
23	Idemat	TU Delft, Netherlands	Y	Y	N	N	Y	N	www.ecocostsv alue.com/EVR/ model/theory/5-Idemat.html Used to select & compare individual materials or processes, designer-oriented.
24	JEMAI -LCA	JEMAI, Japan	Y	Y	Y	Y	Y		www.jemai.or.j p/english/index. cfm No comparisons between produc ts, Japan specific, only available in Japanese.

25	KCL-ECO 3.01	Oy Kesuslaboratorio-Centrallaboratorium Ab (KLC). Espoo, Finland	Y	N	N	N	Y	N	www.ecosmes.net/cm/viewDoc?id=6564&l=EN General
26	LEGEP	LEGEP Software GmbH, Germany	Y	Y	Y	Y	Y	N	www.legep.de/?lang=en Focuses on design, construction, quantity surveying and evaluation of new or existing buildings
27	LC Advantage	Battelle/DOE, USA	Y	Y	Y	N	Y	N	Weak database, US only
28	LC Aid™	DPWS Environmental Services, NSW, Australia	Y	Y	N	N	Y	N	Www.irbnet.de/daten/iconda/CIB10092. Limited to EI 95, waste, waste & energy mostly Australian data can import 3D CAD drawing for building assessment
29	LCAiT	Chalmers Ind. (CIT), Sweden	Y	Y	Y	N	Y	N	Www.ecosmes.net/cm/viewDoc?id=6564&l=EN

									Measuring environmental performance of buildings
30	Life Cycle Explorer	United States	Y	N	N	Y	Y	Y	Prototype used to assess window design options
31	NIRE LCA	NIRE, Japan	Y	Y	N	N	N	N	
32	Open LCA 1.9	GreenDelta GmbH	Y	Y	Y	Y	Y	Y	Www.openlca.org/ General
33	PEMS	Pira International, UK	Y	Y	Y	Y	Y	Y	Limited; Public data only.
34	PT Laser™	Sylvatica, North Berwick, Maine, USA	Y	N	N	N	N	N	Www.ecosmes.net/cm/viewDoc?id=6564&l=EN Limited
35	REGIS	Sinum AG-EcoPerformance Systems	Y	Y	Y	N	Y	N	Www.sinum.com/ General but limited to linear equations
36	REPAQ	Franklin Associates, USA	Y	Y	N	N	N	N	LCI Tool, US/UK data
37	SABENTO	Ifu Hamburg GmbH, Germany	Y	Y	Y	Y	Y	Y	Www.sabento.com Data from literature, strong materials Flow accounting. (Chemical)

38	Sima Pro	PRé-Consultants Netherlands	Y	Y	Y	Y	Y	Y	www.pre-sustainability. com/ General; efficient for all
39	Spine	CPM, Sweden	Y	Y	N	N	Y	N	Http://195.215.251.229/Dotnet nuke/ Data tool, no calculation, just storage and facilitation of d ata collection
40	SULC A	VTT Technical Research Centre of Finland	Y	N	N	N	N	N	https://www.simulationstore.com/sulca General
41	TEAM	Ecobilan/ Ecobalance/ Price Water house Coop ers PW, Europe/US A	Y	Y	Y	Y	Y	Y	Www.ecobilan.pwc.fr/en/boiteaoutils/tem.jhtml Limited
42	TESPI	ENEA, Italy	Y	N	N	N	Y	N	www.elca.enea.it/ General but limited
43	Umbert o	Ifu Hambur g GMBH	Y	Y	Y	Y	Y	Y	www.umberto.de/en Data from literature, strong materials Flow accountin g. General

44	USES-LCA	Netherlands Center for Environmental Modelling	Y	N	N	N	N	N	www.cemnl.eu/ useslca.Html. Terrestrial, freshwater, and marine ecosystems
45	US NREL	USA	N	Y	N	Y	N	N	www.nrel.gov/lci General and limited

ISO –complies with the ISO 14040 standards on LCA

DQA – data quality assessment evaluation

Impacts – Impact Assessment method

Stats – features of simple parameter variations (Monte Carlo)

Y- yes

N- no

Several literatures, papers and books have been reviewed; and the four most prevalent software tools that have withstood the test of time suitable for the cement industry are as discussed in Table 2.3.

Table 2.3: Four most suitable tools for LCA in the cement industry

S/N	Name	Vendor/ Developer	Tool	Database	ISO 14040	Guidelines (DQA)	LCIA	Statistical analysis	Comments
1	GaBi	IKP Uni. Stuttgart/ PE, Germany	✓	✓	✓	✓	✓	✓	www.gabi-software.com General but very suitable for building and assemblies construction

2	OpenLCA 1.9	GreenDelta GmbH	✓	✓	✓	✓	✓	✓	www.openlca.org/ Generic
3	SimaPro	PRé-Consultants Netherlands	✓	✓	✓	✓	✓	✓	www.pre-sustainability. com/ Generic; efficient for all
4	Umberto	Ifu Hamburg GMBH	✓	✓	✓	✓	✓	✓	www.umberto.de/en Data from literature, strong for materials Flow accounting. Generic

The following are characteristic features common to the four software packages:

- These tools present results using a Sankey diagram; this is a good tool for visualizing the influence of each process on the entire impact via the width of the diagram.
- They include an uncertainty analysis that monitors potential distortion in measurement through the Monte Carlo analysis.
- They accommodate the creation of a process that allows for easy calculation.
- They accommodate comparisons between products and processes.
- Results are usually presented in the form of a report as they are often communicated to organizations, associations or another third party.
- They accommodate data quality checks.

- They also allow results to be exported in graphical form and text editor format (Word or Excel and other sources).
- They accommodate minimum requirements, which are the LCI and LCIA.
- The results obtained from the evaluation will be different based on the data provided and the goal definition [55, 75, 78-82].

2.7.1 OpenLCA

This is a freeware package that allows users to evaluate all the stages of LCA with ease. The term freeware refers to any software that can be downloaded from the internet and used for free (which makes it cost-effective). However, it is often a closed source with no stipulated software rights in which case the publisher can retain the copyright of the source codes. This software was developed in 2006 by GreenDelta with the support of PE International (developers of GaBi), PRé Consultants (creators of SimaPro) and UNEP (United Nations Environment Programme) [81]. Some of its features are:
- OpenLCA does not contain any database but works with OpenLCA Nexus (an online repository for LCA data that includes the Ecoinvent database, the ELCD database and the GaBi database primarily). OpenLCA was initially designed for evaluating the environmental impact of products and processes but it can now evaluate LCC [81]. Some of the features of this software are:

- The databases in OpenLCA Nexus do not contain LCIA methods. LCIA methods need to be imported/created manually in each database in OpenLCA to carry out life cycle impact assessment. This comprehensive package of environmental impact assessment methods is formatted for use with all the databases available at OpenLCA Nexus.
- It also allows the graphical presentation of the processes that have the largest impacts and lists all the impacts.
  - With OpenLCA it is possible to create LCA studies compliant with ISO 14040 and 14044 [83].
  - It provides more visual results, even between different products [81].

2.7.2 Umberto

This software was developed by Ifu Hamburg over 25 years ago. Some characteristic features include:

- It is less user-friendly than SimaPro and GaBi and it doesn’t bring significant innovation when compared with the other software [71].
- It is more suitable for flow accounting and processes that involve strong materials.
- It provides the minimum requirements, which are the LCA and LCIA.
- Following installation, the Ecoinvent LCI database and/or the GaBi LCI databases are extracted in the software.
- It considers ISO 14040 guidelines for LCA in its operation [82].

2.7.3 SimaPro

One of the leading software packages that has been useful in the industry and academia for over 25 years in over 80 countries is SimaPro. It was developed by the Pre-Consultants and widely used across the world with continuous improvements in its functionality included from one version to the next. Its latest version is SimaPro 9. The following are some characteristic features of SimaPro:
- SimaPro comes with the Ecoinvent v3.6 database, covering over 10,000 processes.
- It comes with a large number of standard impact assessment methods.
- SimaPro allows you to create completely new methods or delete impact categories/methods.
- It complies with ISO 14040 guidelines for LCA in its operation.
- This tool allows users to customize databases, impact assessment methods and inputs.
- SimaPro allows the graphical illustration of processes that produce high impacts.
- It allows comparison between products with different results and different values.
- It shows a list of all impacts, thus it gives robust but adequate results.
- The SimaPro interpretation stage is designed in the form of a list that covers significant issues mentioned in the ISO 14044 standard.
- Currently, SimaPro can be run in English (UK), English (US), Dutch, Danish, French, German, Italian, Portuguese, Spanish, Swedish and Japanese.

- Both full and quick evaluations can be performed using this software.
- SimaPro also weighs environmental impacts based on additional outputs.
- It allows a pictorial view of an outcome immediately the parameters are changed.
- Results are often presented in the form of reports because they will be communicated to stakeholders.

- It allows recycling and allocation scenarios calculation.
- The software provides European specific LCIA methods [55, 75, 78, 79].

2.7.4 GaBi

GaBi was developed by PE Product Engineering GmBH and IKP Uni. Stuttgart in Germany. This tool has 25 years of experience, 10,000 users in 19 countries and serves more than 2,000 companies. It was developed to allow the user full LCA evaluation as well as Life Cycle Costing (LCC). Its characteristic features are:

- GaBi allows users to customize the database, impact assessment methods and inputs with utmost transparency.
- It is available in English, Japanese and German and used globally [84].

It offers the most instinctive graphical interface for displaying.

- GaBi allows a comparison of the results of different parameters.
- GaBi is a dynamic software tool that allows users to have a pictorial view of an outcome immediately the parameters are changed.
- It considers ISO 14040 guidelines for LCA in its operation.
- GaBi is designed with a text editor which allows editing of tables and graphs, and automatically modifies results when inventory changes.
- GaBi allows the user to carry out non-liner process modelling.
- It allows both recycling loops and allocation calculation.
- The databases available in this software are according to ISO TR 14049 and are hyperlinked to individual datasets using HTML files. This allows data to be traced back to raw materials [84].

- Both full and quick evaluations can be performed using this software.
- GaBi is a complex tool designed for different users and LCA practitioners [84].

- It is highly focused on the automotive and electronics industries and has its major users in these industries. It also has a suite known as the “GaBi Life Cycle Engineering Suite”.

Table 2.4: Summary of some characteristics of selected tools for LCA evaluation

AREA	GABI	OPENLCA	SIMAPRO	UMBERTO
Database	YES	YES	YES	YES
ISO 14040 Guidelines	YES	YES	YES	YES
(DQA)	YES	YES	YES	YES
LCIA	YES	YES	YES	YES
Statistical analysis	YES	YES	YES	YES
Report of results	Self-editor for report Exportation to word/ excel	Graphical Report presentation, custom tables. Exportation to Word/ Excel	Graphical Report presentation with list of impacts. Exportation to Word/ Excel	Graphical Report presentation. Exportation to Word/ Excel
Communication	YES. GaBi users/database users	YES, between SimaPro users and EcoSpold and other tools like CAD	YES EcoSpold ILCD	YES
Graphical interface	Intuitive flow-path, Sankey diagram	Flow-path, Sankey diagram	Flow-path, Sankey diagram	Sankey diagram
Database	Gabi datasets, Ecoinvent, U.S.LCA (NREL)	Ecoinvent, ELCD, and GaBi databases	Ecoinvent, U.S. Input/Output, U.S. LCI, Dutch Input/Output, Swiss Input/Output, LCA food, industry data, Japanese Input/Output, IVAM	Gabi database, Ecoinvent
Comparison of results	YES, product and process	YES	YES, product and process	YES

Table 2.4 summarizes the characteristics of selected LCA tools. Even though OpenLCA is about 41-94% as fast as SimaPro when calculating a large Ecoinvent unit process, it is a freeware package. Life cycle assessment is primarily a tool for decision-making on an issue that is as critical as environmental impact, which is often applicable to a whole nation and will require accurate and comprehensive evaluation using standard software. Thus, extra care should be taken when using such software for important assessments. Although OpenLCA is user-friendly and cost-effective, the database is imported from Nexus and LCIA methods have to be created manually and imported into the database obtained from Nexus. An impact assessment method would have to be created manually for each imported database. ISO requirements can also be created.

Among the other three software (SimaPro, GaBi and Umberto) tools that have been in existence for over 25 years, Umberto is not as robust in its characteristic features compared to the others. Moreover, it is not as user-friendly and does not necessarily bring sufficient innovation when compared to SimaPro and GaBi even though they are of similar prices. GaBi seems to be more robust in its characteristic features but it is too complex to work with. Moreover, it is more focused on the automobile industry and not the cement industry. SimaPro is more suitable for LCA study in the cement industry as it has robust characteristics that comply with almost all the requirements of LCA software as well as software suited for the cement industry with a wide variety of databases. Based on this study, SimaPro software would be recommended as the most suitable LCA software for the cement industry. However, it is worth noting that every user knows what they are looking for in software as well as the required analysis. As stated earlier, the result of an assessment is a function of the goal definitions and databases inputted. Thus, the choice of a software package is left for the user or LCA practitioner to make based on the desired output. This paper will guide the user to tailor their desired outputs to a particular software package that would be most useful based on the available database.

2.8 Conclusion

This chapter has comprehensively reviewed selected literature related to the different applications of LCA of the cement industry and their results. The first part of the review presented detailed information about cement: raw material preparation, production process, energy consumption, CO_2 emission and removal. It also went further to analyze CO_2 emission in the cement industry as the major greenhouse gas emitted by cement production. The next part showed the application of

LCA in the cement industry in some countries and the assessment results. Thereafter, the effect of incorporating BAT and using alternative processes for cement production was analyzed using LCA. A comparison of the effects on environmental impact and the conventional procedures for producing OPC was also carried out. The last section of this chapter reviewed the LCA software packages that are seen as most suitable for the cement industry by first considering the basic requirements of a typical software tool and thereafter analyzing the available LCA software tools to find the best one for the cement industry.

CHAPTER 3

METHODOLOGY

3.1. Introduction

This chapter presents the methodology used for this analysis and extensively explains the pros and cons of using this approach alongside the two approaches that will be used for analysis in this study. The different stages of the life cycle assessment method recommended by the international standard organization (ISO) are described in detail. It also explains the data collection process and summarizes the inventory data of the production cement, which will be incorporated into the LCA software that is described in this chapter.

3.2 Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is a system-oriented approach used for the estimation required to assess the environmental impacts of a product or process by examining all the stages of a production process which begin with the abstraction of raw material (the "cradle") to cement production (the "gate"), to cement application, to the lifespan and thereafter to the end-of-life, or recycling process (the "grave"). This leads to the terms "cradle to gate" or "cradle to grave". LCA was developed over three decades ago primarily to support decision making [75, 85]. LCA gives a holistic view of the entire production process. Effective application of LCA is a function of the intended goal to be achieved in a study. Thus, there is flexibility in the implementation of LCA from one study to another based on the defined goal [32, 33]. In 1997 the International Standards Organization (ISO) established the framework for evaluating environmental and possible other impacts related to a product, process or service to meet the needs of many countries as well as, more specifically, industries. The framework is known as the ISO 14000 series. The ISO 14000 series standards include an instruction o carry out an LCA and serve as a guide for techniques and procedures. However, to eradicate variations among these several ISO standards and to enhance readability, two new international standards for LCA were issued in 2006: ISO 14040 and ISO14044: defined as principles and framework requirements guidelines without requirement respectively [33, 75].

Environmental Management documentation includes further definitions, clarifications, detailed technical descriptions and applications of LCA, that replaced the initial standards [86]. The four stages of LCA recommended by ISO are: Goal and scope definition, Life cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation as seen in figures 3.1 and 3.2 [75, 87].

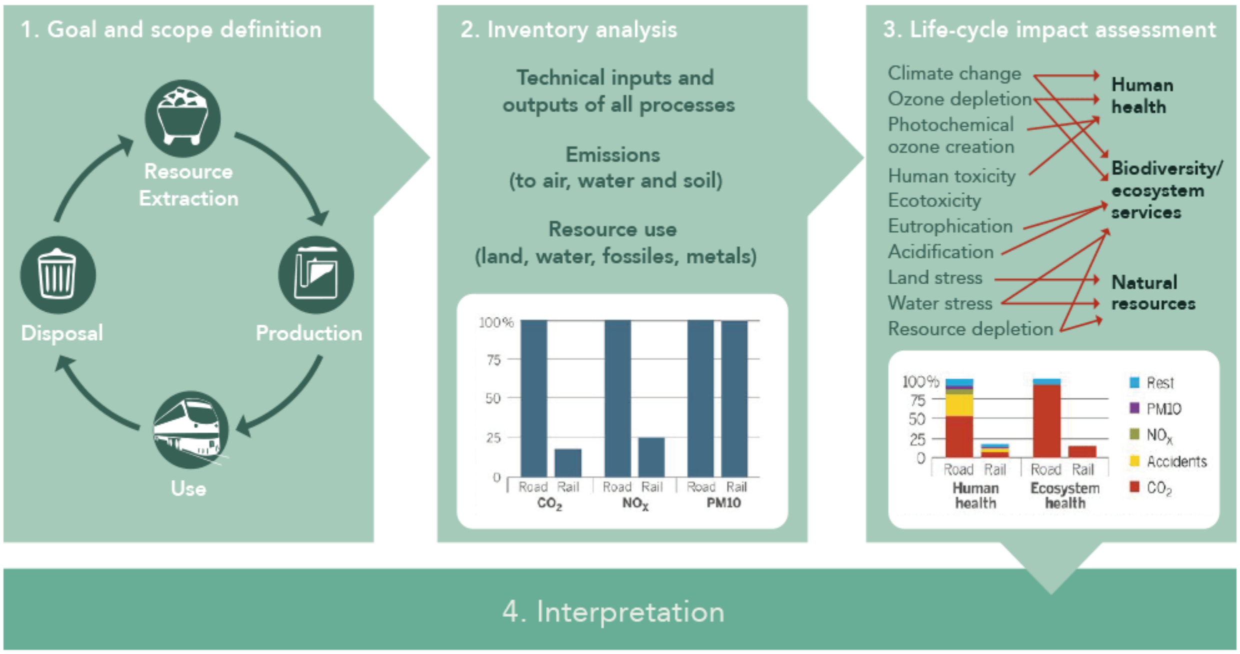


Figure 3.1: Four stages of LCA as they relate to one another [88]

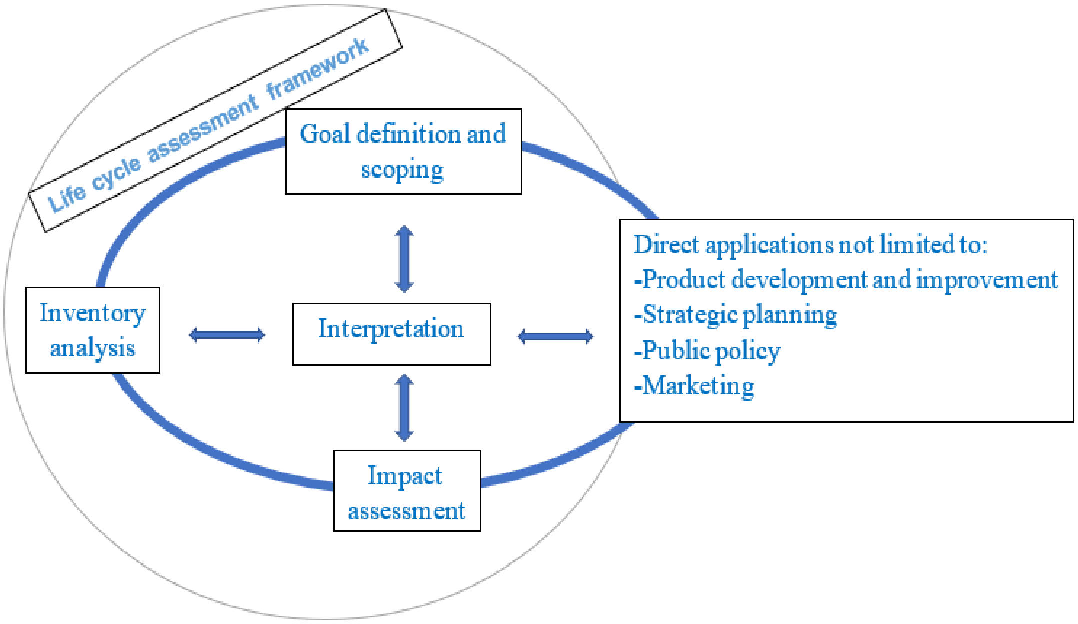


Figure 3.2: Adapted LCA phases and applications [33]

3.2.1 Goal and scope definition

It is of utmost importance to first clearly define the goal when carrying out a life cycle assessment of a process or product. The purpose of the assessment should include what the result/s will be used for and who the result/s users are (the target audience). In a cement industry, the main focus is to assess the environmental impacts based on data made available from the unit production of cement [53] while the scope would be the raw material acquisition, processing and product manufacturing phases [63]. The scope definition of an LCA study describes the jurisdiction of the assessment. The following must be clearly explained in the scope definition: the system to be studied and its function, the functional unit, the system boundaries, the types of impact and impact assessment method, data quality requirements, and the assumptions and limitations [89, 90]. System boundaries refer to what is to be included for consideration or omitted in the system. In addition, the functional unit is a fundamental factor in a study: it clearly explains the measurement used in a system and in this study the measurement used is 1kg of cement produced. The results of the LCA will primarily be translated in the functional unit used; a good example is: if the functional unit is in tons of cement, the results would be in tons as well [75]. In this study, the functional unit is in kg of cement, so the results would be in kg as well. The goal of this study is to carry out a life cycle assessment of 1kg of cement produced in a typical South African cement industry. This study only covered the 'cradle-to-gate' assessment of the production process of cement; the data used from this analysis was from the extraction of raw material through to the production of cement. The packaging, use, disposal/end of life or waste treatment data were not taken into consideration in this study. Also, this study primarily analyzed the environmental impacts with large values that could cause pronounced damage. Impacts with minimal or negligible values were not further analyzed. In addition, when using the two approaches, only characterization and damage categories were considered. Other tiers such as Normalization, Single score and Weighting were not considered in this study so as to reduce possible assumptions and uncertainties. The intended audience of this are researchers, policy makers in South Africa, and cement industry community in South Africa. The intended application of this study is to improve the environmental impacts of the cement industry in South Africa.

3.2.2 Life Cycle Inventory (LCI)

The Life Cycle Inventory (LCI) analysis has to do with the compilation of input and output inventory data that are not only consistent with the product under assessment but equally have several environmental coverages [91]. For the cement industry, a cradle-to-gate inventory involves all the processes, raw materials and essential requirements needed to make cement ready for use, while a cradle-to-grave inventory requires the above-mentioned inventory with extension to useful life and disposal, or recycling. Tools and software are available to assist [75]. There are no grounds for assessing potential environmental effects or even room for improvement without an LCI. The quality of the data will reflect throughout the entire LCA stages from this point. Figure 3.3 is a graphical illustration of how the four stages interplay.

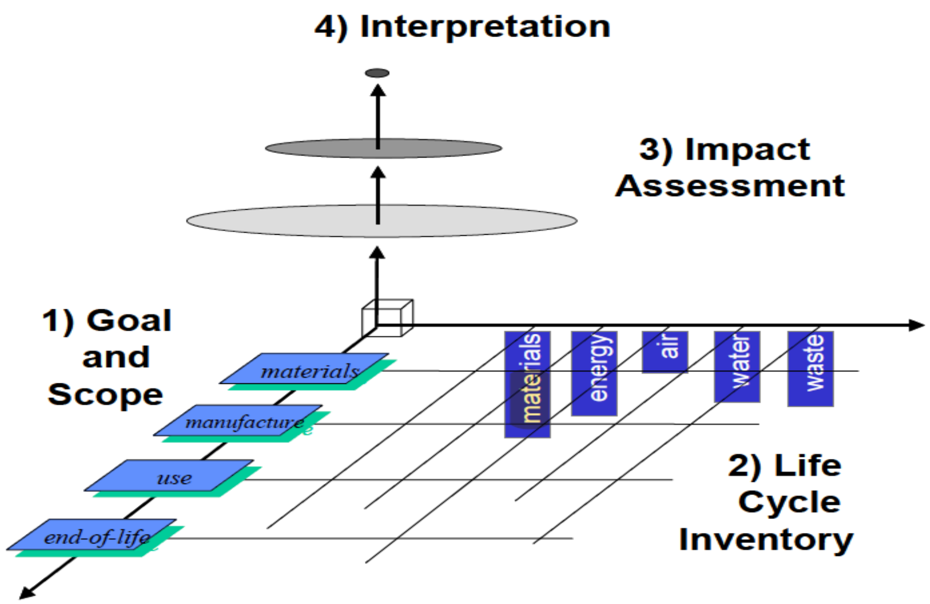


Figure 3.3: Graphical illustration of how the four stages of LCA interplay with basic resources [75]

3.2.3 Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment is a multiple-issue tool used to evaluate potential environmental impacts in line with environmental resources (inputs and outputs) identified in the life cycle inventory. This assessment addresses several environmental issues such as energy, climate change, water pollution, etc., thus allowing for comprehensive evaluation of the impacts of the system [75, 92]. This is an attempt to establish the connection between a product and its potential environmental impact [85]. The impact assessment is divided into classification, characterization and valuation [93] as seen in Table 3.1 below. Characterization is the summation of data that are within the impact groups by using equivalency factors [93]. Basically, it is a quantifiable phase that evaluates the comparative influence of the several inputs or outputs by groups [94]. Vitally, characterization aims to pattern each model after scientific knowledge as much as possible [89]. Valuation can either be qualitatively or quantitatively carried out by professional groups or by the evaluation of environmental loading profiles, respectively [95].

Table 3.1: LCA structure as proposed by the society of environmental toxicology and chemistry (SETAC) as adapted by [93, 95, 96].

Analysis	Goal definition and scope
	Inventory analysis
Assessment	Impact assessment divided into:
	Classification
	Characterization
	Valuation
Interpretation	Improvement analysis

The evaluated impacts are classified into three groups: human health, ecological health and resource depletion in order to have a proper description of its effects as analyzed in a product [95]. The life cycle impact assessment (LCIA) stage is a multifaceted process that groups all inventory into their various impact categories. Thereafter, a sensitivity analysis is conducted at the final stage where the LCIA and LCI results are interpreted as well. LCA is an assessment tool for analyzing the environmental implication of a process or product by taking cognizance of the potential effect of the entire cycle chain of such process or product, which is cement in this case. One good position LCA takes in a system study is to give a holistic LCIA method. LCA calculations (environmental impacts) are based on definite factors. This helps to speed up the analysis as well as simplify the system studied. Basically, there are two approaches in LCIA: the problem/process-oriented approach (midpoint) and the damage-oriented approach (endpoint). The life cycle assessment expert can use either of them for evaluation [97]. Midpoint and endpoint approaches are characterization models that indicate the effects at different levels. ReCiPe has two meanings: it presents the recipe for calculating LCIA and is also an acronym for the developers, which are RIVM and Radboud University, CML and PRé Consultants[97]. The development of ReCiPe was mainly the result of the need to harmonize the midpoint and endpoint methods and consequently break the barrier of the selection of LCIA method in the LCA model [98]. ReCiPe is an attempt to make available the evaluation of both the midpoint and endpoint approaches in a coherent manner; however, the implementation of these approaches may give dissimilar interpretations.

In the midpoint approach, flows are categorized into the environmental impact to which they contribute. This approach presents about 18 impact categories which cover several impacts: global warming, stratospheric ozone depletion, ionizing radiation, ozone formation (human health), ozone formation (terrestrial ecosystem), fine particulate matter formation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, marine toxicity, water consumption, fossil resource scarcity, mineral resource scarcity, land use, etc. [98]. This approach helps to simplify numerous flows by streamlining them into a few prevalent environmental impacts.

The midpoint approach gives a cause−effect evaluation right from the emission of substances or the use of resources [99]. The midpoint (process oriented) approach presents the results of the impact categories in two tiers i.e., characterization and normalization. Normalization in midpoint is based on the normalization factor, which is the particular percentage of damage per capita, that is, the combination of different impact categories. Therefore, only characterization will be analyzed in detail in this study to reduce uncertainties (as the normalization value might not be accurate, absolute or wholesome) and also for proper understanding.

The endpoint approach, on the other hand, considers mostly the areas of damage, and simplifies flow to evaluate impacts at the area of significance to life (AoSL): human health, ecosystem, resources [100], giving a slightly easier result interpretation. In the human health category, ReCiPe uses disability-adjusted life years (DALY), which means the years of life lost or the years of damage to life due to environmental impacts. The ecosystem damage category uses species lost within a specified time period due to emissions into the environment, water body, etc. The resources damaged category is based on economic loss due to a marginal increase in costs (measured in USD) as a result of resource extraction [23, 98, 101]. Endpoint helps to answer the question: “Why should I worry about global warming or terrestrial acidification?” Although the endpoint approach gives insight into damages caused, it may neglect to mention some environmental impacts, which is in contrast to the midpoint approach which gives a wide coverage of environmental impacts [102]. The endpoint approach uses characterization, damage categories, damage normalization, weighting and single score all with their factors set either by the individual or the software (based on the inventory used). Damage to the area of significance to life will be the major focus in this study. The midpoint approach is a more scientific approach while the endpoint approach should be an addendum [103].

One of the leading software packages that has been useful in both the industry and academia for over 25 years in over 80 countries is SimaPro. It was developed by the Pre-Consultants and widely used in the world with continuous improvement in its functionality from one version to the other [75]. Its latest version is SimaPro 9.0. It comes with a large number of standard impact assessment methods with ReCiPe included. SimaPro allows the user to create completely new methods or delete impact categories/ methods. It complies with ISO 14040 guidelines for LCA in its operation. This tool allows the user to customize the database, impact assessment methods and inputs [78]. SimaPro allows the graphical illustration of processes that produce high impacts. It allows comparison between products having different results and different values. Thus, it gives a robust yet adequate result by listing all the impacts. SimaPro also weighs environmental impacts based on additional outputs. It allows for a pictorial view of an outcome immediately the parameters are changed [55, 79]. The software used for the LCA in this study is SimaPro 9.1.1. ReCiPe was used as the LCIA method in this study because it provides both midpoint and endpoint results. ReCiPe uses a cultural theory as three models are used to qualify three basic assumptions and considerations [104]. Individualist (I) considers the short-range impact as a result of the most significant chemicals. Egalitarian (E) is based on a preventive measure that considers the lasting perception and implies risk. Hierarchism (H), on the other hand, is a well-adjusted perspective whose basis is prevalent policy values [79]. Also, ReCiPe provides another set of weighting factors (A) by averaging the weighting factors of the three viewpoints. The balanced term H is the default and recommended choice. The average value will also be adopted in this study. The ReCiPe Midpoint (H)-World and ReCiPe Endpoint (H)-World H/A are, therefore, used in this study for the assessment of ordinary Portland cement. This study aimed to use both the midpoint (problem-oriented) and endpoint (damage-oriented) approaches of ReCiPe to assess the environmental implication of OPC and make recommendations. In recent times different studies have been done on the environmental impacts of cement. However, the adoption of both the midpoint and endpoint approaches when using the LCIA method is not prevalent in those studies. Until now, very few studies that make use of both midpoint and endpoint in the analysis of Portland cement have been conducted. Thus, there was a need to carry out a study in this area.

3.2.4 Interpretation

Interpretation, which is the last of the stages, is an efficient method used to evaluate, compute and categorize the results from the information provided by the life cycle inventory (LCI) and the life cycle impact assessment (LCIA) and relate to it effectively [105]. In this phase, the expert identifies important environmental pointers (e.g., energy, CO_2 gases), important influences on these pointers, and important unit processes in the cycle. A good example of what the expert does in a situation where the result shows a great value for global warming potential is to trace the assessment back to the LCI in order to identify the particular unit process that produces the output resulting in that hotspot. The interpretation requires that the sensitivity of the results is examined, a scenario analysis performed, the quality of data reviewed, and the result aligned to the goal of the study [75]. The following are the two objectives of life cycle interpretation as outlined by the International Organization for Standardization (ISO):

• To clarify limitations, evaluate results, draw conclusions, present a lucid result and proffer recommendations on the basis of the outcomes of the stages of the LCA [85].

• To readily offer a logical, comprehensive and reliable results presentation of the LCA study with regard to the stated goal and scope [33]. The SimaPro interpretation stage is designed in the form of a list that covers significant issues mentioned in the ISO 14044 standard. Results are often presented in the form of reports because they will be communicated to stakeholders.

3.3 Uncertainty analysis

Uncertainty analysis is a systematic technique used investigate the level of ambiguity that exist in a set of variables used in models for the purpose of decision-making. Physical (observation) or experimental measurements are used for uncertainty analysis. In relation to this study, uncertainty analysis will be in terms of the level of uncertainty that has been incorporated into the LCI as a result of a number of factors ranging from uncertainty in input, inconsistency of data, imprecision of model, etc. [33]. In his work in 1998, Huijbregts presented six kind uncertainties: uncertainty due to choices, model uncertainty, parameter uncertainty, variability between objects and sources, spatial variability and temporal variability [72]. There are several approaches for carrying out this analysis; one of the prevalent approaches is Monte Carlo simulation which is a statistical modeling method. This approach has been incorporated into the SimaPro software; however, it has its application in some LCA studies [70, 106]. An uncertainty analysis was carried out in this study using Mote Carlo simulation in order to measure the level of uncertainties of the result seeing that a secondary data was used for the analysis (though the uncertainty of the inventory data had been adjusted appropriately). The uncertainty analysis was carried out with 1000 iterations and 95% confidence interval.

3.4 Conclusion

This chapter has detailed the approach selected to achieve the objectives of the research. The LCA is an excellent tool to analyze the entire production cycle of a product or process. This chapter has explained in detail the four stages of LCA: goal and scope definition, LCI, LCIA, and interpretation; how they interrelate to one another and how they are applied in this study. Also, the two LCIA methods available in ReCiPe were well established to illustrate its application in this study. Worthy of note is the LCA software: SimaPro, whose characteristic features were enumerated to establish its adequacy for this study. The last part of this chapter reviewed the LCA software packages considered most suitable for use in the cement industry by first considering the basic requirements of typical software and thereafter analyzing the available LCA software tools to ascertain which was the best one for the cement industry.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter begins by giving a brief overview of the South African cement industry and gives details about concepts such as functional unit, boundary and production processes; it also provides information on the inventory data used for the analysis. The LCA of both midpoint and endpoint is presented in a comprehensive yet easy-to-understand manner showing the different impacts. The substances that contribute to these impacts and their consequent effects are also shown. The chapter concludes by stating the damage these impacts can cause to human health in South Africa, the ecosystem and resources by interpreting each of the results and thereby showing the need for mitigation.

4.2 South African cement industry overview

The cement industry in South Africa is one of the largest in Africa and in the southern African region. The cement market experienced an exponential growth of about 69% between 2008 and 2014 and was forecasted to stabilize by 2019 [107]. Between 2012 and 2015 the sales of cement experienced a total annual growth rate of 3.9% with a relatively high resilience as importation affected local production. Against the norm, retailers as opposed to cement producers controlled about 70% of cement sales. This value implied a 40% increase in its price as at 2011 [108]: this showed the high level of importation into SA. Other customers were ready-mix concrete suppliers, concrete product manufacturers and construction companies [109]. Continuous increase in competition has resulted in a huge reduction in price and this has made the system unsustainable as the return on investment is lower than the industry's capital cost as the current cost of cement is about R790 per ton on average [110]. This has, therefore, necessitated initiatives for optimizing costs. In 2008 Portland cement (CEM 1) accounted for over 50% of cement sales and was predicted to account for 90% of the market by 2019 [107]. This made it the most prevalent cement type.

There has been a continuous increase in the clinker-mix replacement of about on average 30-40% since the 1990s. This has resulted in the annual reduction of greenhouse gas emission [111]. The cement industry in South Africa accounted for 1% of the country's greenhouse gas emission. According to the reports issued by the Department of Environmental Affairs 2014 [112], between 2000 and 2010 the annual greenhouse gas emission from cement production increased by 27% from 3.3MT CO_2e to 4.2MT CO_2e. By this time Portland cement (which does not allow clinker replacement) was becoming the most prevalent product). Also, the annual emission mitigation potential of the cement industry would be 1.26 MT CO_2e, 3.65 MT CO_2e, and 15 MT CO_2e by 2020, 2030 and 2050 respectively. This study therefore intended to carry out a life cycle assessment (LCA) of the South African cement industry, and analyze the environmental impact using the LCIA midpoint and endpoint approaches.

4.3 LCA of 1kg of Portland cement produced in the South African cement industry

4.3.1 Background information

The study aimed to prioritize specific impacts (impacts with high value) and discuss remedies to reduce these impacts so as to make meaningful recommendations on the most appropriate mitigation measures. It focused on identifying environmental impacts and hotspots emanating from the South African cement industry. This analysis embraced the cradle-to-gate approach of LCA without providing packaging and dispatching information. This was because cement has several end-of-life applications and obtaining data for such an application would be difficult; therefore, a cradle-to-grave analysis could not be conducted. The mass-based functional unit used in this study is the kilogram thus 1kg of Portland cement produced in a South African cement plant was used. Appendix 1 and Appendix 2 give detailed information about the inventory database used for this analysis. Figure 4.1 gives a summarized material flow diagram for the production of 1kg of Portland cement.

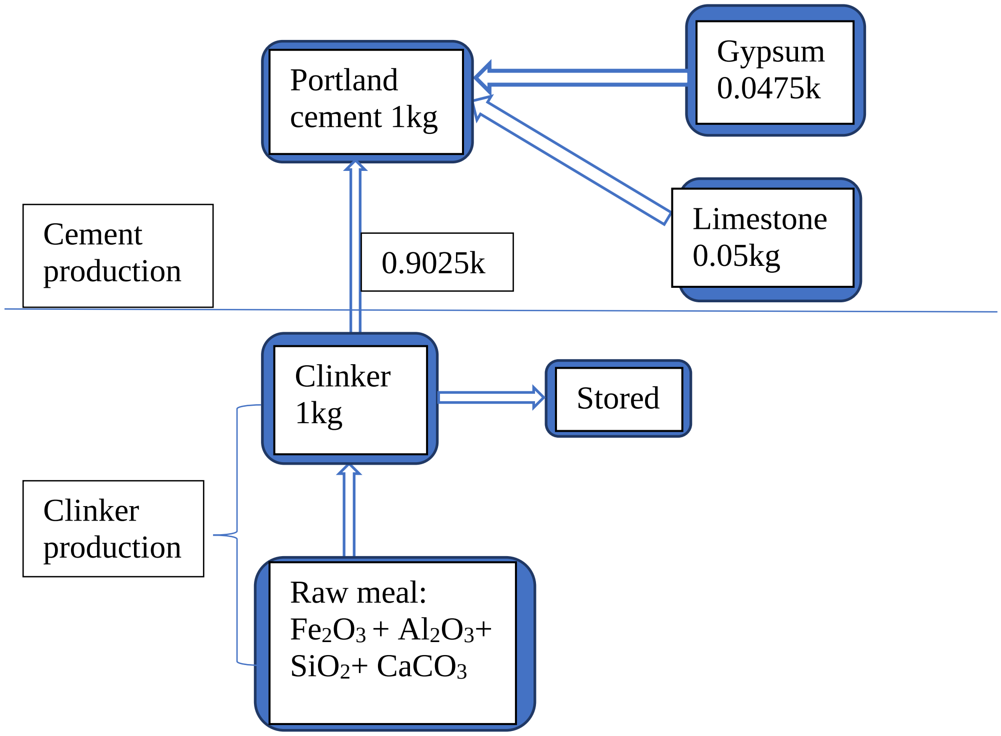


Figure 4.1: Material flow diagram for the production of 1kg of Portland cement (adapted from the Ecoinvent database) [113, 114]

The entire production process is basically divided into two phases: clinker production and cement production (they are produced separately). Therefore, Appendix 1 represents the comprehensive data of clinker production, while Appendix 2 represents the comprehensive data of cement production.

4.3.2 Midpoint analysis (process-oriented approach)

In the midpoint approach, flows are categorized into the environmental impact to which they contribute. This approach presents about 18 impact categories which cover several impacts: global warming, stratospheric ozone depletion, ionizing radiation, ozone formation (human health), ozone formation (terrestrial ecosystem), fine particulate matter formation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, marine toxicity, water consumption, fossil resource scarcity, mineral resource scarcity, and land use. This approach helps to simplify numerous flows by streamlining them into a few prevalent environmental impacts.

Figure 4.2 represents the contribution of five production processes to the impact categories. These five production processes are: (1) Clinker production (2) Raw material consumption (3) Electricity usage (4) Fuel consumption and (5) Transportation where clinker production includes calcination and burning of fuel. The evaluation and interpretation are as explained below.

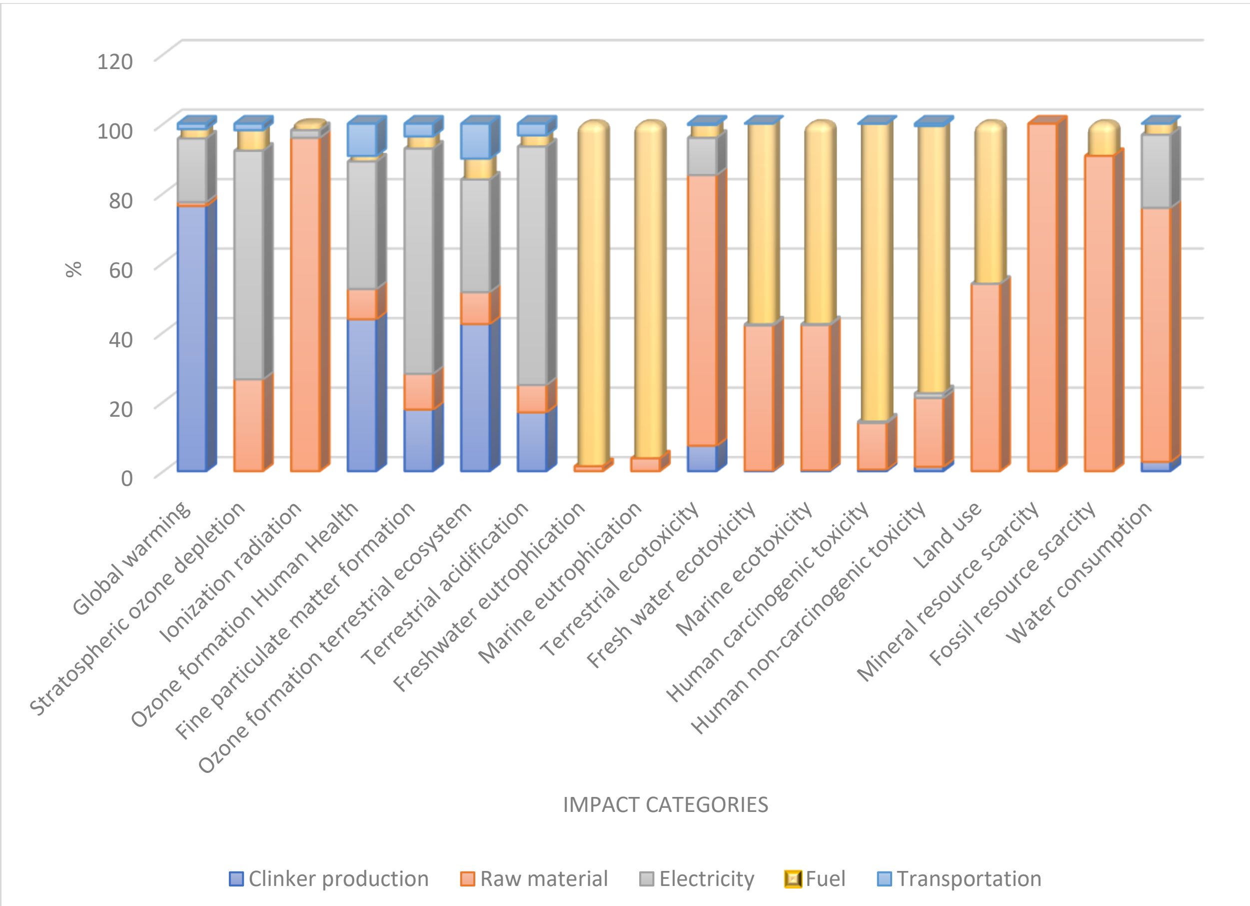


Figure 4.2: Contribution of five production processes to impact categories (midpoint)

4.3.2.1 Clinker production

As presented in Figure 4.2 the clinker production stage has made a large contribution to global warming. It contributes 76.3% to the global warming impact category. In ozone formation (human health) and ozone formation (terrestrial), clinker production contributes 42.6% to each impact category. Fine particulate matter formation, terrestrial acidification, and terrestrial ecotoxicity contribute 17.7% 16.9%, and 7.3% respectively.

The contribution of clinker production to fresh water ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, and water consumption are 0.005%, 0.116%, 0.43%, 1.23% and 2.6% respectively: the contribution is really minimal. Clinker production did not contribute at all to the stratospheric ozone depletion, ionization radiation, marine eutrophication, land use, mineral scarcity and fuel resource scarcity impact categories.

4.3.2.2 Raw material consumption

As seen in figure 4.2, Raw material consumption contributed to all the impact categories. The largest contribution is seen in Mineral scarcity: 99.99%, Ionization radiation: 95.9%, Fresh water scarcity: 90.7%, Terrestrial ecotoxicity: 77.9%, and Water consumption: 73.1%. Other relatively large contributions are made by Land use: 53.9%, Fresh water ecotoxicity: 41.9%, and Marine ecotoxicity: 41.9%. Raw material consumption has made a minimal contribution to Stratospheric ozone depletion: 26.4%, Human non-carcinogenic toxicity: 19.8%, Fine particulate matter formation: 10.3%, Ozone formation terrestrial ecosystem: 9.2%, Ozone formation Human health: 8.7%, Terrestrial acidification: 7.9%, Marine eutrophication: 3.67%, Freshwater eutrophication: 1.4%, and Global warming, 1.2%. The highest effect of raw material consumption is seen in mineral scarcity: 99.99%.

4.3.2.3 Electricity usage

As seen in figure 4.2 Electricity usage contributed 68.6% to Terrestrial acidification, 65.8% to Stratospheric ozone depletion, and 64.8% to Fine particulate matter formation. Electricity usage had a minimal contribution to Ozone formation Human health: 36.7%, Ozone formation terrestrial: 32.4%, Water consumption: 21.04%, Global warming: 18.3%, and Terrestrial ecotoxicity: 10.7%. The contribution of electricity usage to Ionization radiation was: 2.2%, Human non-carcinogenic toxicity: 1.38%, Human carcinogenic toxicity: 0.38%, Freshwater ecotoxicity: 0.32%, and Marine ecotoxicity: 0.26%. The impact categories are minimal. Electricity usage did not contribute at all to Freshwater eutrophication, Marine eutrophication, Mineral scarcity, or Freshwater scarcity.

4.3.2.4 Fuel consumption

Fuel consumption made a significant contribution to Freshwater eutrophication as seen in Figure 4.2. Other contributions were seen in Human carcinogenic toxicity: 85.7%, Human non-carcinogenic toxicity: 76.9%, Fresh water scarcity: 57.765%, Marine ecotoxicity: 57.7% and Land use: 46.1%. Minimal contributions were made to Fresh water ecotoxicity: 9.3%, Ozone formation terrestrial: 6%, Stratospheric ozone depletion: 5.9%, Terrestrial ecotoxicity: 3.7%, Marine eutrophication: 3.67%, Fine particulate matter formation: 3.5%, Terrestrial acidification: 3.2%, Water consumption: 3.2%, Global warming, 2.7%, Ionization radiation: 1.9%, and Ozone formation Human Health, 1.6%,

4.3.2.5 Transportation

As seen in figure 4.2, the transportation usage contribution to the impact category was minimal. The contributions made were 3.4% to Terrestrial acidification, 1.9% to Stratospheric ozone depletion, 3.7% to Fine particulate matter formation, 9.3% to Ozone formation Human health, 9.3% to Ozone formation terrestrial, 0.02% to Water consumption, 1.6% to Global warming, 0.4% to Terrestrial ecotoxicity, 0.69% to Human non-carcinogenic toxicity, 0.05% to Human carcinogenic toxicity and 0.005% to Fresh water ecotoxicity.

Table 4.1: Characterization results of the environmental impacts of 1kg cement (midpoint)

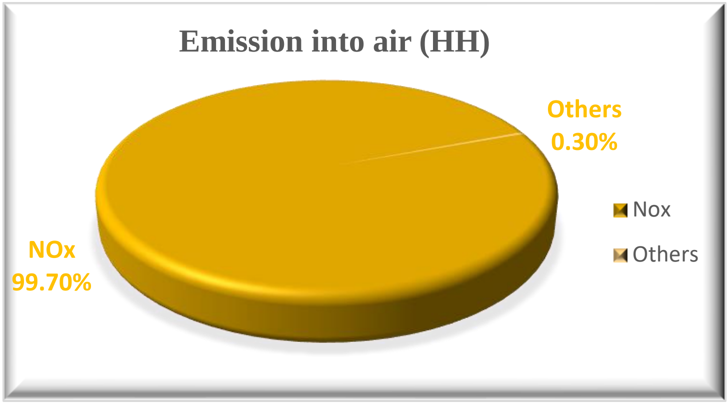
S/N	Impact category	Unit	Cement Portland {ZA}
1	Global warming	kg CO_2 eq	0.993
2	Stratospheric ozone depletion	kg CFC11 eq	1.94E-7
3	Ionization radiation	kBq Co-60 eq	0.00997
4	Ozone formation, Human health	kg NO_x eq	0.0021
5	Fine particulate matter formation	kg PM2.5 eq	0.000793
6	Ozone formation, Terrestrial ecosystem	kg NO_x eq	0.00212
7	Terrestrial acidification	kg SO_2 eq	0.00244
8	Freshwater eutrophication	kg P eq	0.000316
9	Marine eutrophication	kg N eq	1.93E-5
10	Terrestrial ecotoxicity	kg 1,4-DCB eq	1.04
11	Freshwater ecotoxicity	kg 1,4-DCB eq	0.0158
12	Marine ecotoxicity	kg 1,4-DCB eq	0.0214
13	Human carcinogenic toxicity	kg 1,4-DCB eq	0.0244
14	Human non-carcinogenic toxicity	kg 1,4-DCB eq	0.497
15	Land use	m2a crop eq	0.00783

16	Mineral resource scarcity	kg Cu eq	0.00216
17	Fossil resource scarcity	kg oil eq	0.139
18	Water consumption	m^3	0.00136

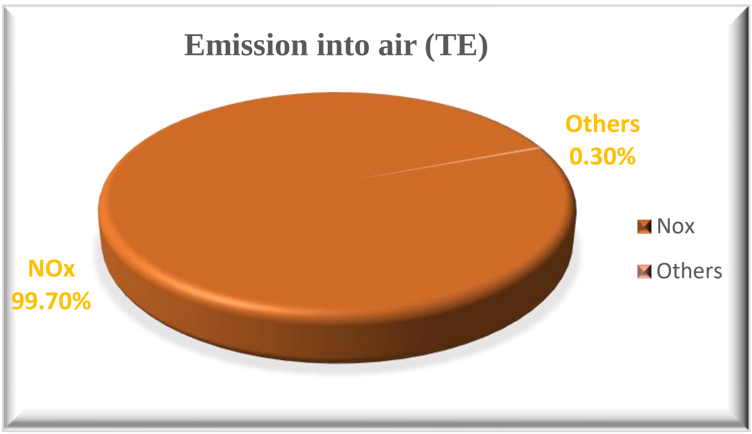
The characterization results of the environmental impacts of 1kg of cement using midpoint are shown in Table 4.1 for every 1kg of cement produced. Impacts with the same units were further grouped into: Ozone formation and toxicity, while the individual impacts on Global warming, Ionization radiation, fine particulate matter formation, Terrestrial acidification, Freshwater eutrophication, Marine eutrophication, water consumption, land usage, Fossil resource scarcity, Mineral resource scarcity remained the same. The grouped impacts were further analyzed. Global warming and Fossil resource scarcity will also be further analyzed because its impact value was very high compared to the remaining impact categories.

4.3.2.6 Ozone formation

This includes Ozone formation, Human health (HH) and Ozone formation, Terrestrial ecosystem (TE). The formation of ozone formation ultraviolet (UV) radiation occurs naturally, which interacts with oxygen. Ozone layer formation is a protective mechanism to prevent the ash effect of UV radiation on the Earth. The anthropogenic ozone formation starts with the emission of nitrogen oxides (NOx) and/or the non-methane volatile organic compound (NMVOC) into the atmosphere and with chemical reactions, the ozone layer is formed. The high concentration of ozone formation in the atmosphere affects both humans and species (the ecosystem). Its effect is seen in health complications and even the death of species. As seen in Table 4.1, the environmental impact is seen in two phases with respect to human health and terrestrial ecosystem. We see that for every 1kg of cement produced, 0.00421kg of NOx eq is emitted into the atmosphere and its effect is seen as ozone formation.



(a)



(b)

Figure 4.3: Substances contributing to the ozone formation impact category (a) HH impact category, (b) TE impact category

NOx is one of the major air pollutants where its chemical reaction with oxygen in the atmosphere can produce nitrogen dioxide and increased concentration of this in the human system has a comprehensive list of possible complications. NOx has both direct and indirect effects on humans: direct effects because it can affect human health and indirect effects because it affects the ecosystem, which humans, plants and animals, both aquatic and non-aquatic, depend on. Further analysis was done on Ozone formation, Human health and Ozone formation, Terrestrial ecosystem to find what percentage of NOx was causing this impact category and to which sub-compartment it was emitted into. The result of the analysis is presented in Figure 4.3. We can see that this impact category is the result of the emission of 99.7% of NOx into the atmosphere. Nitrogen oxides have the capacity to form smog as well as acid rain when emitted into the atmosphere. Also, when they react with volatile organic compounds (VOCs), ammonia, and some other compounds, they can form particulate matter (PM2.5) small enough to pass through the nasal cavity and which can easily penetrate the sensitive parts of the lungs thereby causing respiratory complications.

Also, as seen in figure 4.1, in both cases it was realized that about 42.6% of the emission of the NOx was from the clinker production stage and about 37% of the emission was from the electricity consumption stage.

4.3.2.7 Toxicity

This includes Marine ecotoxicity, fresh water toxicity, Terrestrial ecotoxicity, Human carcinogenic toxicity and Human non-carcinogenic toxicity. Toxicity hazardous stressors have the potential to cause harm to the ecosystem and consequently to humans through either physical, chemical or biological platforms. Calculations of human toxicity potential show the potential harm that a chemical unit emitted into the environment can cause based on the innate toxicity of such chemical substance. These platforms, which can also be referred to as toxicants, are not limited to physical, chemical or biological platforms; they can also be in the form of radiation or even behavioral changes. Terrestrial ecotoxicity encompasses toxicity to aquatic and non-aquatic species, organisms in the soil and plants and so on. Continuous dwindling of Terrestrial ecotoxicity is therefore important as it in turn affects humans. Also, toxicity to waterbodies describes the effect of toxic compounds on aquatic organisms when released into the water. Often, an outbreak of disease into the aquatic community is ascribed to food and water as these are the major platforms for an encounter with toxic substances. Carcinogenic substances are insidious in nature and are not at any given time toxic at all. They, however, have terminal effects which often result in death. They are substances or radiation, which are primarily involved in the formation of cancer. Cancer is a disease that damages the normal cells which then do not undergo normal cell death but instead multiply repeatedly.

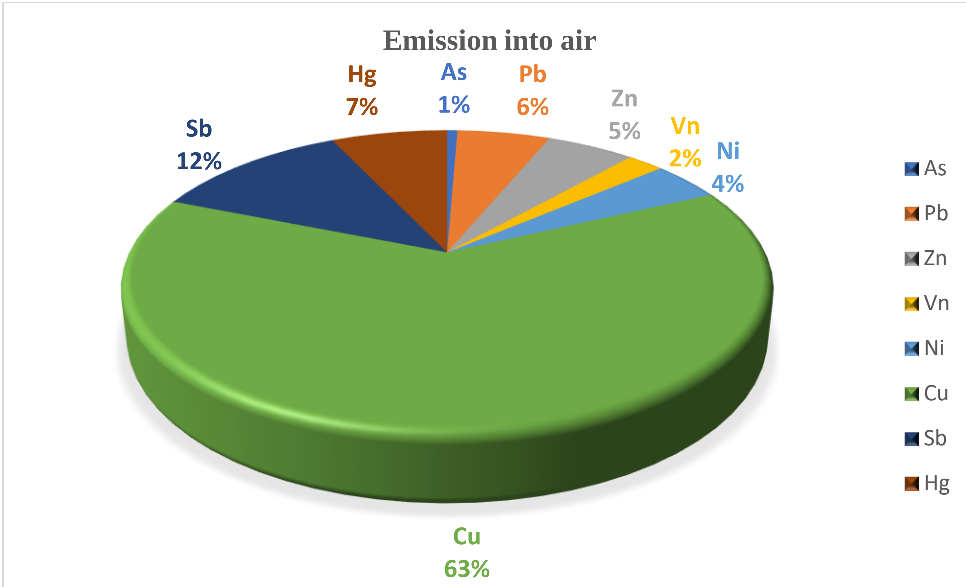


Figure 4.4: Substances contributing to toxicity: Terrestrial ecotoxicity impact category

With humans, toxicants can either be carcinogenic or non-carcinogenic in nature yet still be very harmful. As seen in Table 4.1, for every 1kg of cement produced, about 1.6kg of 1,4-Dichlorobenzene (1,4-DCB) eq is produced and its effect is seen in the toxicity of humans, waterbodies and the ecosystem as a whole. 1,4-DCB is an inorganic compound with high malodour and consists of molecules of benzene and chlorine. Terrestrial ecotoxicity and Human non-carcinogenic toxicity were further analyzed, as they have significant value when compared to the others, to ascertain the actual substance that is released into the environment, their percentage, and sub-compartments of emission.

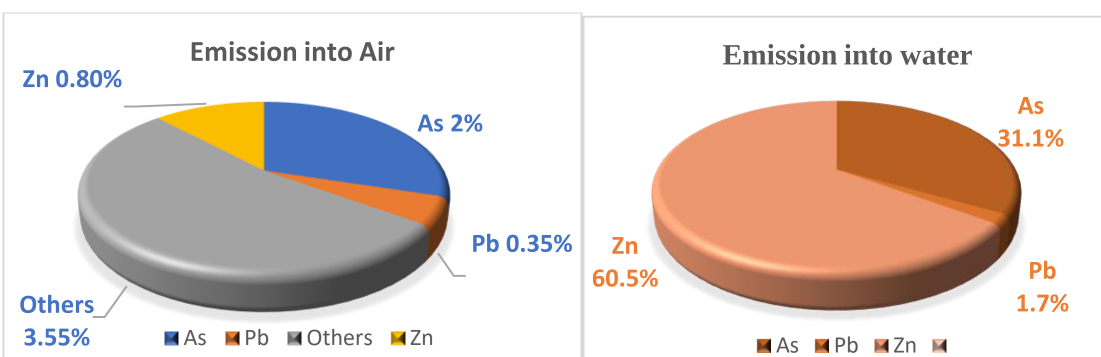


Figure 4 5: Substances contributing to toxicity: Human non-carcinogenic toxicity impact category

Figure 4.4 represents the results of the analysis of Terrestrial ecotoxicity. In Table 1 we see that 1.04 of 1,4-DCB eq was produced; this is as a result of 63% of copper, 12.3% of antimony, and 7.1% of mercury being emitted into the atmosphere as shown in figure 4.4. These are strong chemicals that are common pollutants and are toxic to the environment. Although copper is needed for cellular metabolism, it has the capacity to cause brain impairment and also interfere with normal brain development. Human non-carcinogenic toxicity is mainly emitted into water but also into the air. In Table 1 we see that 0.49 kg of 1,4-DCB eq was produced for every 1kg of cement produced; this was as a result of 60% of zinc, 31% of arsenic and 1.7% of lead being emitted into the water body and a very minimal amount of this substance being emitted into the air as seen in figure 4.5. In high concentration, zinc presents a severe level of toxicity. As much as it is needed by organisms for metabolism, it is only needed in trace amounts and a high concentration is deadly to organisms.

4.3.2.8 Global warming

The concept of global warming and its relationship with changes in climatic conditions is fast becoming a highly relevant topic that has created awareness globally. In nature some gases are present in the atmosphere to serve as an umbrella-like covering for protection from the effects of solar energy experienced on earth. This greenhouse effect causes the energy from the sun to be trapped by these gases and prevented from escaping from the earth, thereby keeping the planet a warm and habitable place for both humans and the ecosystem. This explains why they are referred to as greenhouse gases (GHG). These GHGs are emitted into the atmosphere naturally from animals and trees and can also be emitted through anthropogenic activities from automobiles, burning of coals etc. Continuous increase in such anthropogenic activities will signify a high concentration of greenhouse gases in the atmosphere and this will consequently trap more heat, thereby causing the planet to be warmer or causing changes to the natural climatic patterns thus, changes in climatic conditions [115] [116]. This process is known as global warming. Therefore, temperatures that are normally experienced during the day or during specific climatic seasons (winter and summer) are typically higher due to climate change.

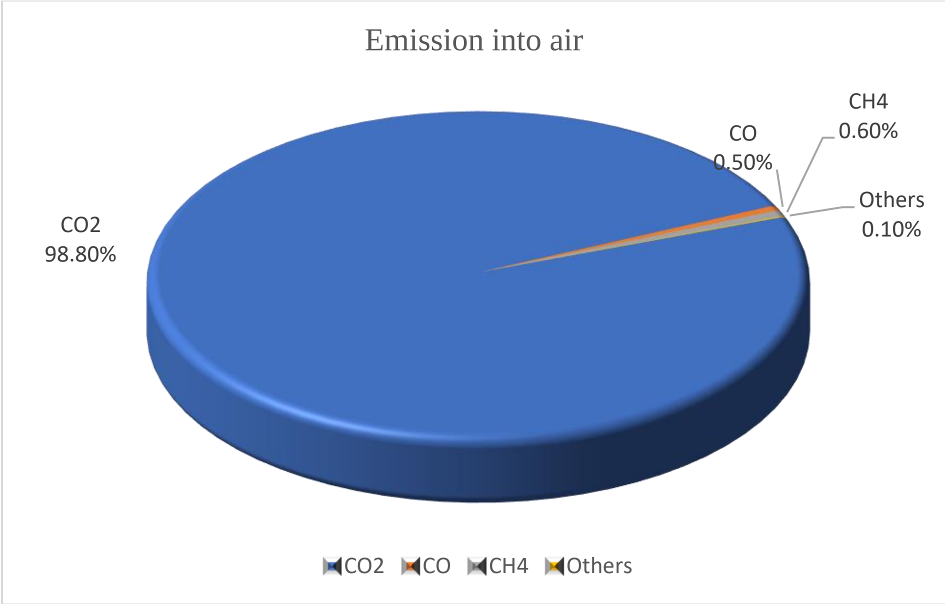


Figure 4.6: Substances contributing to global warming

As seen in Table 4.1, 0.993kg of CO_2 eq was produced for every 1kg of cement produced and its effect has been seen in global warming. Of this value, 78.3% was contributed at the clinker production stage while 18.3 % was from electricity and the rest of the percentages were from raw material consumption, fuel consumption and transportation. Further analysis of global warming was carried out and the results are as presented in figure 4.6. The results show that CO_2, CO and CH_4 were emitted in the following percentages: 98.8%, 0.5% and 0.6%, respectively and 98.8% (0.981kg of CO_2) of 99.3kg of CO_2 eq was from the emission of CO_2 gas. This implies that for every 1kg of cement produced, 0.981kg of CO_2 was emitted and the effect of this emission can be seen in global warming.

Apart from the climatic changes that can be caused by a high concentration of greenhouse gases in the air, they have wide-ranging effects on human health and the environment. These gases contribute to respiratory diseases arising from air pollution and smog (as in the case of ozone formation). Increase in wildfires can also be an effect of GHG. CO_2 plays a major role in air pollution as a result of the global warming effect. It forms ozone at ground level by trapping radiation and is absorbed by the oceans from the atmosphere, thereby increasing the temperature of the water body and over time incapacitating the water body's ability to be able to absorb essential CO_2 needed by aquatic organisms for growth and proper metabolism. This effect is known as ocean acidification. The most significant threat caused by increased CO_2 emission is the greenhouse effect resulting in changes in weather conditions. CO_2 gives rise to the continuous growth of plants. More and more plant areas will exhibit loss of water vapour via the stomata of the leaves: this is known as transpiration. However, a high concentration of CO_2 reduces the water vapour lost by the plants into the atmosphere due to low stomata conductance to water vapour. In addition, exposure to CO_2 can have a wide range of negative effects on human health.

4.3.2.9 Fossil resource scarcity

Fossil resources (fuel), typically crude oil, petroleum and natural gas are not infinite in nature. They will run out after protracted use globally. Currently, about 80% of global source energy comes from fossil resources and over 40% of this energy source comes from oil. Fossil fuels are used by about 90% of the transport sector. These resources are carbon-based substances that react with organic substances in the presence of sunlight. This process is known as the geological process.

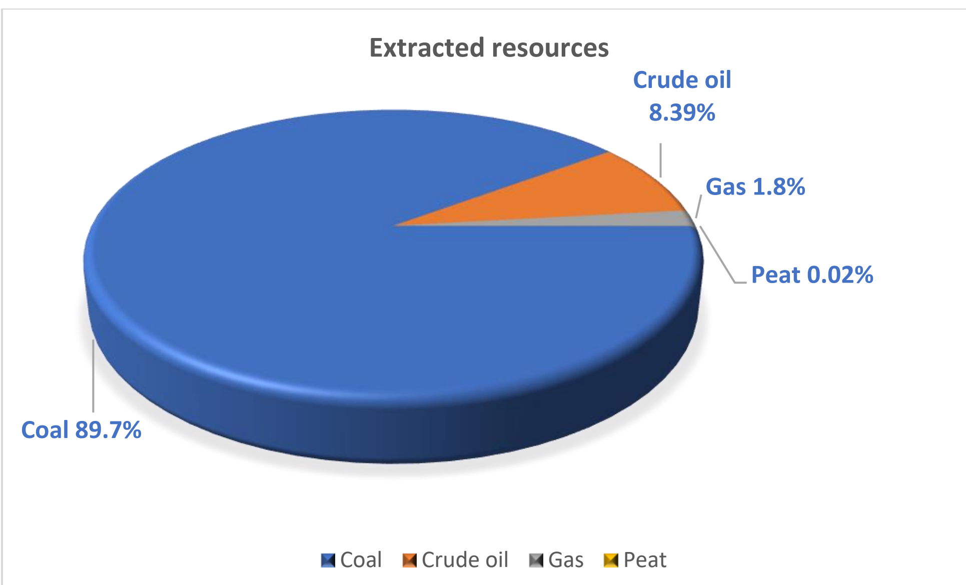


Figure 4.7: Substances contributing to fossil resource scarcity

Fossil resource scarcity begins to occur when demand becomes higher than supply, thereby resulting in a reduction of the resource's available stock. This will consequently lead to a rise in the price of the resources, which may be unsustainable and unaffordable. When a resource becomes relatively scarce and thus more valuable, people might decide to hoard it, making it even more expensive. As seen in table 4.1, for every 1kg of cement produced, 0.139kg of oil eq is produced and its effect is seen in fossil resources scarcity. A further analysis was carried out on this impact category and the result of this analysis is shown in figure 4.7 where the 89.7 % of 0.139kg scarcity is from the burning of coal. Other percentage sources are crude oil: 8.3%, gas: 1.89%, and peat: 0.02%.

Typically, coal is one of the major sources of energy in South Africa. Over 77% of primary energy in South Africa comes from coal. Coal is mostly made up of carbon but contains other elements such as sulphur, nitrogen, oxygen and hydrogen. When burnt, coal emits nitrogen oxides, nitrous oxides (N_2O) and sulphur dioxide (SO_2). SO_2 causes respiratory diseases in humans and also contributes largely to acid rain. N_20 is about 300 times more potent than CO_2 in its ability to cause global warming and also has the capacity to reduce the ozone layer. Burning of coal has a wide range of impacts on both humans and the environment, ranging from various health issues to the greenhouse effect, to climate change, to acid rain and finally to air pollution. A need to have a sustainable source of energy is therefore imperative.

4.3.3 Endpoint analysis (damage-oriented approach)

The endpoint approach, on the other hand, categorizes flows into 22 impact categories. These impacts are thereafter classified into their damage categories. Impacts are simplified into the damage of three areas of significance to life (AoSL): human health, the ecosystem and resources.

Table 4.2: Characterization results of the environmental impacts of 1kg cement (midpoint)

S/N	IMPACT CATEGORY	UNIT	PORTLAND CEMENT
1.	Global warming, Human health	DALY	9.21E-7
2.	Stratospheric ozone depletion	DALY	1.03E-10
3.	Ionizing radiation	DALY	8.46E-11
4.	Water consumption, Human health	DALY	1.5E-9
5.	Ozone formation Human health	DALY	1.91E-9
6.	Fine particulate formation	DALY	4.98E-7
7.	Human carcinogenic toxicity	DALY	8.1E-8
8.	Human non-carcinogenic toxicity	DALY	1.13E-7
9.	Global warming, Terrestrial ecosystems	Species/yr	2.78E-9
10.	Global warming, Freshwater ecosystems	Species/yr	7.6E-14
11.	Ozone formation Terrestrial ecosystems	Species/yr	2.73E-10
12.	Terrestrial acidification	Species/yr	5.18E-10
13.	Freshwater eutrophication	Species/yr	2.12E-10

14.	Marine eutrophication	Species/yr	3.29E-14
15.	Terrestrial ecotoxicity	Species/yr	1.19E-11
16.	Freshwater ecotoxicity	Species/yr	1.09E-11
17.	Marine ecotoxicity	Species/yr	2.25E-12
18.	Land use	Species/yr	6.95E-11
19.	Water consumption, Terrestrial ecosystems	Species/yr	20.1E-11
20.	Water consumption, Aquatic ecosystems	Species/yr	2.14E-15
21.	Mineral resource scarcity	USD2013	0.0005
22.	Fossil resource scarcity	USD2013	0.0164

The characterization result of the environmental impacts of 1kg of cement using the endpoint approach is presented in table 4.2. The analysis of the impact categories based on the five production processes is presented in figure 4.8. The result follows the same trend as that of the midpoint approach but with four other impacts: Global warming Freshwater ecosystems, Water c onsumption Terrestrial ecosystems, Water consumption Aquatic ecosystems, and Freshwater eutrophication. The various impacts presented in Table 4.2 are classified into their damage categories based on the area of significance to life as seen in Table 4.3.

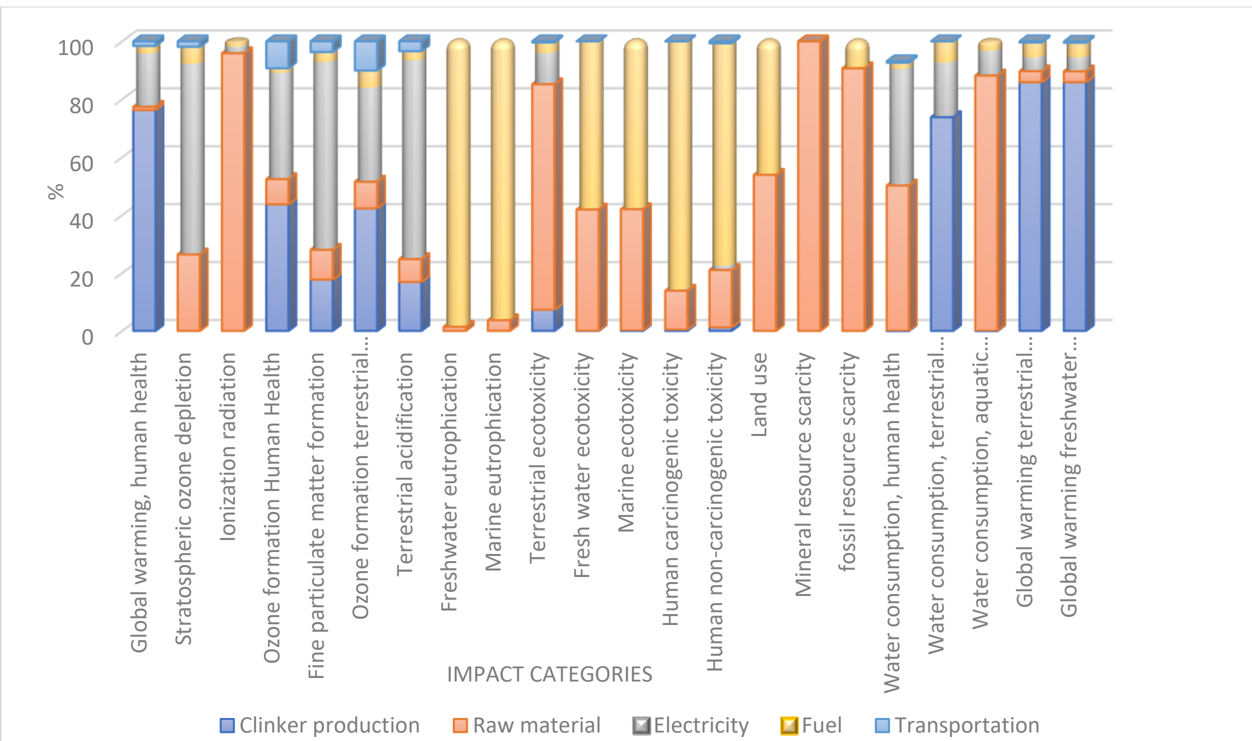


Figure 4.8: Contribution of five production processes to impact categories (Endpoint)

The damage categories: Human health, ecosystems and resources were evaluated and interpreted for five production processes. Figure 4.8 represents the contribution of the five production processes to the damage categories. These five production processes are: (1) Clinker production (2) Raw material consumption (3) Electricity usage (4) Fuel consumption and (5) Transportation. The evaluation and interpretation are as explained below.

Table 4. 3: Classification of impacts into damage categories

S/N	Damage category	Unit	Cement Portland {ZA}
1	Human health	DALY	1.62E-6
2	Ecosystems	Species/yr	3.9E-9
3	Resources	USD2013	0.0169

4.3.3.1 Clinker production

As presented in Figure 4.9, the clinker production stage contributed 49.4% to Human health and 60% to the Ecosystem but did not make any contribution to Resources.

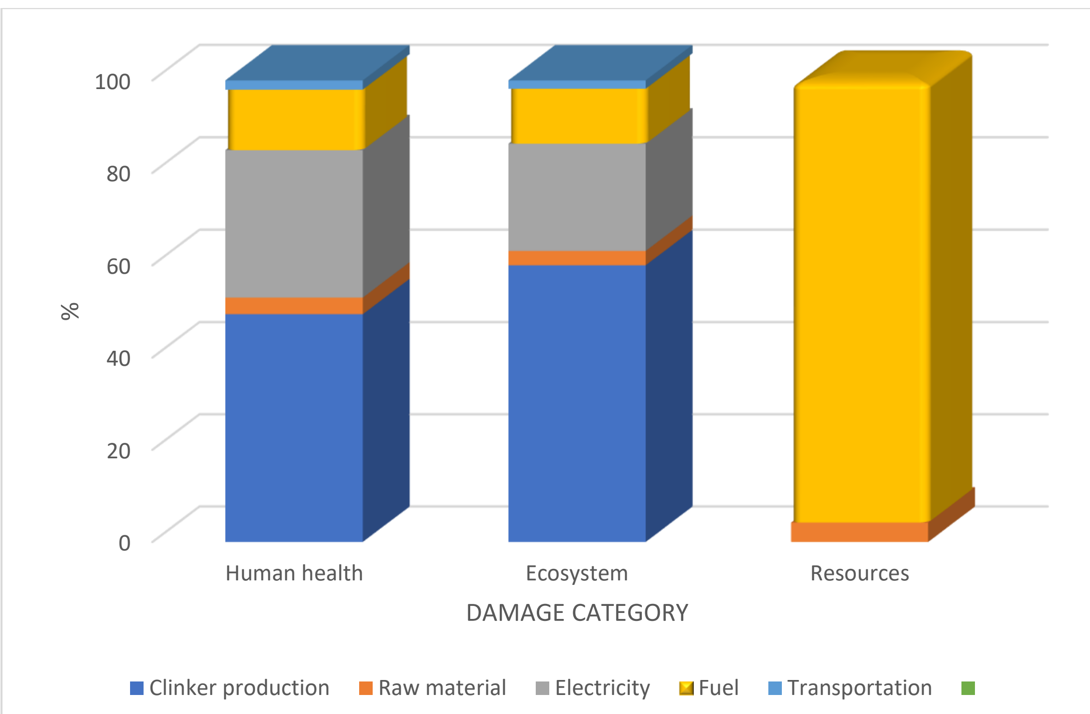


Figure 4.9: Contribution of five production processes to damage categories

4.3.3.2 Raw material consumption

As seen in figure 4.9, the Raw material consumption contributed to all the impact categories: 3.6% to Human health, 3.1% to the Ecosystem and 4.2% to Resources. Overall, the contribution of raw material consumption to the damage categories was minimal.

4.3.3.3 Electricity usage

As seen in figure 4.9, Electricity usage did not contribute damage to Resources but contributed 31.9% to Human health and 23.2% to the Ecosystem.

4.3.3.4 Fuel consumption

Fuel consumption contributed to the three damage categories but made a significant contribution to damage to the ecosystem. As seen in Figure 4.9, 13.1% of its contribution to damage was to Human health, 11.9% to the Ecosystem and 95% to Resources.

4.3.3.5 Transportation.

As seen in figure 4.9, transportation usage contributed minimally to the damage categories. The contributions were 2% to Human health 1.8% to the Ecosystem and no contribution to Resources. The damage category was further analyzed and the result of the analysis is as explained below.

4.3.3.6 Human health

As seen in table 4.3, the damage to human health was 1.62E-6 DALY. DALY was defined by the World Health Organization as the annual summation of potential life lost due to pandemic or disease or another phenomenon. This means that for every 1kg of cement produced, 1.62E-6 lives are endangered. This might seem almost negligible until we consider the population of South Africa and the annual amount of cement required per individual. In concrete production, cement, sand and water are present in the ratio of 1:1.5:3. A medium grade concrete (M20-M30) would contain a maximum quantity of cement of approximately 19% when cement wastage is also considered [117-119]. As at today, concrete is the most produced and consumed material and second only to the consumption of water with about three tons used for every individual annually [120]. We can therefore say that 0.57ton of cement is needed by every South African annually. The latest recorded population of South Africa is about 60 million. This means that 34.2 MTs of cement is needed in South Africa in a year. This translates to about 55404 DALY, that is, about

55 404 lives are potentially endangered due to damage as a result of the annual cement production requirement in South Africa.

This has a very significant impact on South African lives. Figure 4.10 below represents further analysis carried out on the human health damage category of substances that cause these damages and the mediums in which they were expressed where A represents air and W represents water. The results showed that 1% of ammonia was emitted into the atmosphere, 10% of NOx was emitted into the atmosphere, less than 2.5 micrometers of particulate matter was emitted into the air, 2% of arsenic was emitted into the water body, 56% of CO_2 was emitted into the air and 8% of other substances was emitted into both the air and water. The consequence of all these emissions, as explained earlier in the midpoint analysis, is damage to human health.

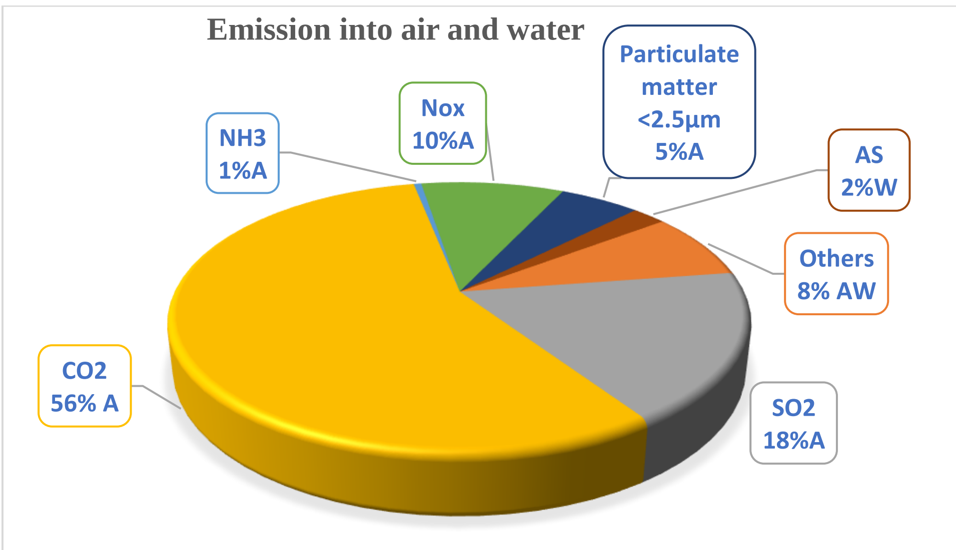


Figure 4.10: Substances contributing to the Human health damage category

4.3.3.7 Ecosystem

As seen in table 4.3, the damage to the ecosystem is 3.9E-9 Species/year. This damage was measured based on the number of species endangered per year. This means that for every 1kg of cement produced, 3.9E-9 species have the potential to die every year. In SA, where about 34.2 MTs of cement is needed every year, about 133 species will potentially be endangered.

Figure 4.11 represents further analysis carried out on the ecosystem damage category on substances that cause this damage and mediums in which they are expressed where A represents air and W represents water. The results showed that 9% of SOx was emitted into the atmosphere, 10% of NOx was emitted into the atmosphere, 5% of phosphorus was emitted into the water body, 71% of CO_2 was emitted into the air and 5% of other substances was emitted into both the air and water. The consequence of all these emissions, as earlier explained in the midpoint analysis, is damage to the ecosystem.

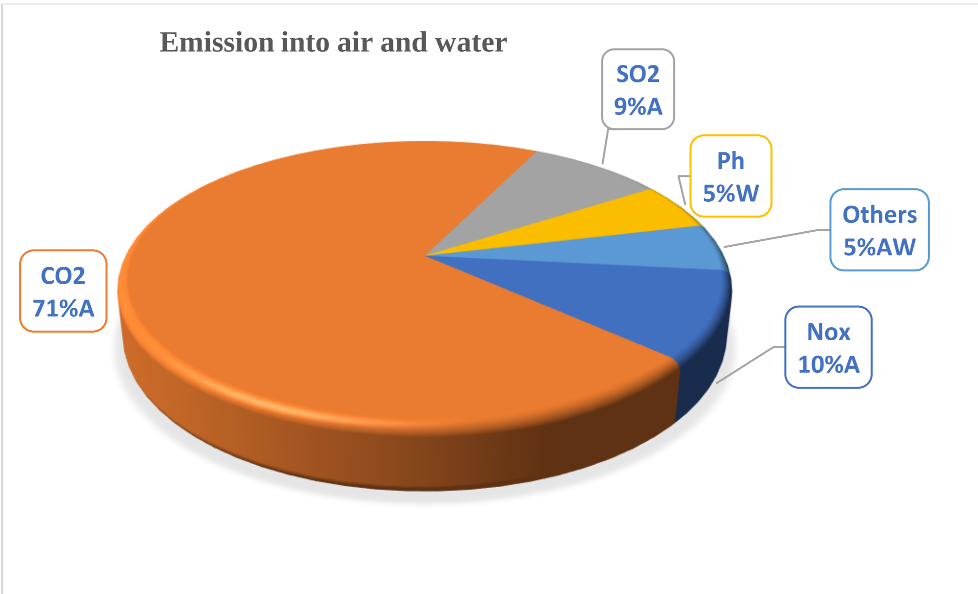


Figure 4.11: Substances contributing to the ecosystem damage category

4.3.3.8 Resources

As seen in table 4.3, the damage to resources was 0.0169 USD at 2013. This represents the potential marginal increase in the cost of resources as a result of the scarcity of such resources. As at 2013, 1 USD was equal to 10.5 Rand. This means that for every 1kg of cement produced, there was potential scarcity of resources, resulting in the potential increase in marginal cost of 0.18 Rand. In South Africa, where about 34.2 MTs of cement is required every year, there would be a potential scarcity of resources causing inflation of the price of these resources by R6.2 billion.

This signifies the potential increase in the cost of resources based on the annual production of cement in South Africa and consequently the annual requirement of resources. This is because these resources are finite in nature and can be exhausted, therefore creating a need for a sustainable source of resources. Figure 4.12 represents further analysis carried out on the resources damage category. The result showed that 60% of the resources in question was for coal, 32% was for crude oil, 6% was for natural gas and 2% was for aluminum.

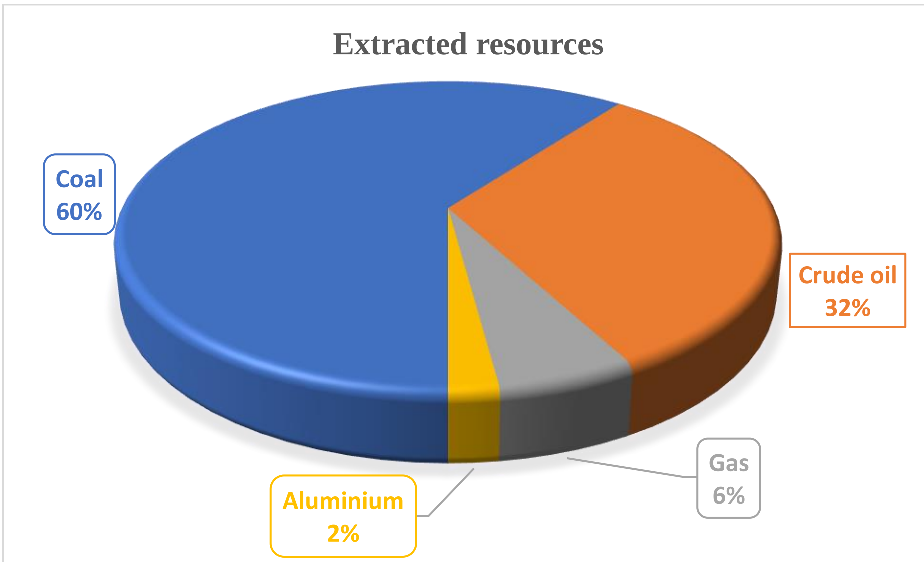


Figure 4.12: Substances contributing to resource damage category.

4.4 Uncertainty analysis Result

The results of the uncertainty analysis are as presented in Appendix 3. The uncertainties of midpoint, endpoint and damage assessment are shown in table 1, table 2 and table 3 respectively.

In the uncertainty result of the midpoint assessment, Water consumption, ecosystems, Human carcinogenic toxicity, ionizing radiation, Freshwater ecotoxicity, Freshwater eutrophication, Human non-carcinogenic toxicity, Marine ecotoxicity have high degree of uncertainty. The same trend is seen in the uncertainty result of the endpoint assessment: Water consumption for Terrestrial ecosystem, Water consumption for Human health, Water consumption for Aquatic ecosystems, Human carcinogenic toxicity, ionizing radiation have high degree of uncertainty while Freshwater ecotoxicity, Freshwater eutrophication, Human non-carcinogenic toxicity, Marine ecotoxicity have relatively high degree of uncertainty. All other impact categories in the approaches were relatively low. Also, in the damage assessment uncertainty result, the uncertainty was averagely low.

4.5 Conclusion

This chapter presented a critical analysis of the impact of a typical South African cement plant using the midpoint and endpoint approaches of LCIA method. The chapter commenced by giving an overview of the cement industry in South Africa. This was followed by the analysis. The production processes were categorized into five major processes: clinker production, raw material consumption, electricity usage, fuel consumption and transportation. The contribution of these production phases on each impact category was analyzed using both approaches. In the midpoint approach, impacts were categorized into 18 flows while in the endpoint approach, impacts were categorized into 22 flows. Impacts were further grouped and analyzed in respect of the substances causing these impacts. In the endpoint analysis, the 22 impact categories were further classified into damage categories based on their effects. The damage categories were divided into the three areas of significance to life: Human health, the Ecosystem and Resources. This chapter wrapped up with a brief discussion on uncertainty analysis result. This analysis gave insight into why there should be concern about these impacts by showing the direct and indirect effects they have on the environment, natural resources and human beings.

CHAPTER 5

CONCLUSION

5.1 Introduction

This chapter concludes this study. It outlines the key findings of the study as well as the various impacts identified by the midpoint and endpoint approaches and also considers the damage categories in the endpoint analysis: it also illustrates the potential damage to South Africans, the species and resources in the natural environment. In conclusion, this chapter makes recommendations on improvement of some of these impacts and further studies. Recommendations are made in two parts: mitigation and adaptation.

5.2 Conclusion

This study presented a life cycle assessment of the environmental impacts caused by a typical South African cement plant used as the case study. The process-oriented (midpoint) and damage-approach (endpoint) of LCIA were adopted in this study so as to present a comprehensive understanding of these environmental impacts. Due to the lack of on-the-ground data, this investigation was carried out using the Ecoinvent database (v3.7.1). The Ecoinvent database was recently considered to be one of the best databases for construction materials and over almost 70% of database users of LCA rely on this database [121]. The inventory data for cement production in South Africa from Ecoinvent is primary data that was taken from five cement plants that represented 90% of the market share of the cement industry in South Africa. The clinker production data was collected separately and stored before it was used for the cement production assessment. The clinker production data is primary data taken from a cement plant that represented 15% of the South African cement market share. A cradle-to-gate analysis was carried out from raw material extraction to cement production. Cement packaging and administrative data were not considered in the analysis.

One of the high points of this study was the impact analysis. The purpose of this assessment was to correctly quantify the environmental impact of cement production. With proper quantification, we can establish what improvements have been made so far and what improvements need to be made in future, thereby making sound recommendations on the way forward to achieve effective mitigation of the environmental impact of cement production. The LCA was carried out on 1kg of Portland cement using the midpoint and endpoint approaches. In both the midpoint and endpoint approaches, the analysis was carried out based on the contribution of five production processes to the impact categories and also the damage categories in endpoint. These production processes were: (1) Clinker production (2) Raw material consumption (3) Electricity usage (4) Fuel consumption and (5) Transportation.

The results showed that the clinker production stage contributed 76.3% to global warming. Raw material consumption contributed 99.9% to mineral scarcity, 95.9% to ionization radiation, 90.7% to fossil resource scarcity and 77.9% to terrestrial ecotoxicity. Fuel consumption contributed 98.6% to freshwater eutrophication, 96.3% to marine eutrophication, 85.7% to human carcinogenic toxicity and 76.9% to human non-carcinogenic toxicity. In addition, electricity usage contributed 65.8% and 64.8% to stratospheric ozone depletion and fine particulate matter formation respectively.

The details of the different impact categories were explained. In midpoint analysis explanation is based on specific substances emitted and the consequence of their emission into air and water or their extraction from the ground. The endpoint analysis on the other hand described why we should be concerned about these impacts by showing us how these impacts affect us directly. The analysis also showed the damage done to human lives, the environment and the economy in terms of the value of our resources. From the characterization results of the midpoint analysis, for every 1kg of cement produced, terrestrial ecotoxicity, global warming, human non-carcinogenic toxicity and fossil resource scarcity with impact values of 1.09kg 1,4-DCB, 0.993kg CO_2 eq, 0.497kg 1,4-DCB, 0.139kg oil eq respectively were found to have the highest impact values. All the environmental impacts from these analyses were grouped based on their units; the grouped impacts and the individual impacts with high value were further analyzed. These impacts are in respect of: Ozone formation, Toxicity, global warming and fossil resource scarcity. Ozone formation includes Ozone formation, Human health, Ozone formation, and Terrestrial ecosystem; Toxicity includes Marine ecotoxicity, fresh water toxicity, Terrestrial ecotoxicity, Human carcinogenic toxicity, and Human non-carcinogenic toxicity. These impacts were further analyzed to find the specific substances causing the impacts and the medium through which these substances were emitted.

From the analysis of ozone formation, it was realized that a high concentration of ozone formation in the atmosphere affects both humans and the ecosystem. It was observed that for every 1kg of cement produced, 0.00421kg of NO_x eq is emitted into the atmosphere and its effect is seen as ozone formation. Though 0.00421kg seem minimal it is worth noting that concrete is fast becoming the most produced substance on earth as about 1 ton is produced for every human being annually. There is a continuous emission and accumulation of nitrogen oxides in the atmosphere and thus there is a need to reduce it to the barest minimum. This was later confirmed in the endpoint analysis on damage made to the ecosystem; one of which was emission of NO_x.

Toxicity can be defined as hazardous stressors which impact both humans and the ecosystem and can lead to a pandemic among humans and even aquatic animals. The analysis showed that for every 1kg of cement produced, 1.6kg of toxicity in the form of 1,4-Dichlorobenzene (1,4-DCB) eq was produced. The Terrestrial ecotoxicity Human non-carcinogenic toxicity impact category was further analyzed. In the case of Terrestrial ecotoxicity, 63% of 1.04 kg of 1,4-DCB eq was as a result of the emission of copper into the air; 12.3% and 7.1% was as a result of the emission of antimony and mercury respectively into the air. With Human non-carcinogenic toxicity, 60%, 31% and 1.7% of 0.497kg of 1,4-DCB eq was the emission result of zinc, arsenic and lead respectively into the waterbody. A high concentration of zinc is deadly for organisms and can cause brain impairment in humans.

One of the major effects of global warming is climate change caused by the greenhouse effect. The result of the analysis showed that for every 1kg of cement produced, 99.3kg of CO_2 eq was emitted; 78.3% was contributed by clinker production and the effect was global warming. Further analysis presented that of this 99.3kg of CO_2 eq, 98.8% (0.981kg) was actually from CO_2. Meyer's report stated that almost 1 ton of CO_2 is emitted for every one ton of cement produced [122]. This implies that for every 1kg of cement produced, 0.981kg of CO_2 is emitted and the effect of this emission is seen in global warming. In the endpoint analysis, CO_2 contributed 56% and 71% damage to human health and the ecosystem respectively. In both the midpoint and endpoint analysis, CO_2 had the highest emission value.

In the recently concluded review studies of American academics, it was established that exposure to atmospheric CO_2 in a poorly ventilated environment has the potential to cause harm to the human body even in low concentrations [123]. The range of effects on human health is limitless. Evidence shows that high concentrations of less than 5000 ppm of CO_2 pose a high health risk. Other indications are that CO_2 concentration with poor ventilation poses the same risk and the current concentration in an indoor environment has already exceeded this concentration. Statistics have shown that a typical urban environment already has emissions of 2100 ppm of CO_2 and increased concentration will pose a greater threat. This is the case globally and nothing like it has been seen in the previous 200 decades: the alarming incidence of rising temperatures is also now more than it has been in the previous 200 decades [124].

For every 1kg of cement produced, 0.139kg of oil eq is used and its effect is seen in the scarcity of fossil resources. In the midpoint analysis, 89.7 % of the cause of fossil resource impact was as a result of extraction of coal while in the endpoint analysis, it was realized that coal extraction contributed 60% to the damage to resources. This is because over 77% of energy sources in South Africa comes from coal. Combustion of coal emits SO_2 and N_2O. SO_2 contributes largely to acid rain and also causes respiratory disease; N_2O, on the other hand, is a greenhouse gas and its potential to contribute to global warming is 300 times higher than CO_2 although it has a shorter lifespan. It is estimated that South Africa's coal reserves have been reduced to about 53 billion tons. With the current rate of production, coal will likely only be available for the next 20 decades.

The origin of fossil fuels can be traced back as far back as 66-541 million years ago but in about the next 20 decades, with the current rate of production, oil, natural gas and coal will be exhausted in 53, 54 and 110 years respectively [125]. Moreover, in the endpoint analysis of resources, it was discovered that 60% of the damage caused was because coal was extracted from fossil resource.

In the endpoint analysis, 1kg of cement was analyzed based on damage to the area of significance to life, damage to human health, the ecosystem and resources. They are expressed in DALY, species/year and USD2013 respectively. The analysis showed that 0.0169 USD2013, 3.9E-9 Species/year and 1.62E-6 DALY are the damages made to resources, the ecosystem and human health respectively. The latest recorded population of South Africa was about 60 million and seeing that about three tons of concrete is needed by every individual annually, which contains only about 19% of cement [126], this study was able to estimate the damage caused to human health, the ecosystem and resources based on the cement production requirements in South Africa. From the analysis, about 55,404 DALY: 55,404 is the potential number of lives that could be endangered based on annual cement production in SA. With respect to the ecosystem, the estimation showed that about 133 species are potentially endangered, while for resources, the effect of the potential scarcity of resources would cause a total marginal price increase of R6.2 billion based on the annual cement production requirements in SA.

Noteworthy is the fact that South Africa relies on clinker and cement importation. Therefore, the empirical values obtained from this analysis might not necessarily translate into real values. The various impacts and damage indicators shown in this study represent a need for effective reduction and mitigation.

Most of the above results are in line with previous studies [53, 56, 58, 69, 70, 127, 128]. The variations experienced in some of the results are as a result of plant/quarry location, proximity to resources (raw materials and fossil fuels) and electricity sources. There are differences in the transportation systems, type of fuel used, electricity generation-mix, etc.; thus, a difference in values can be justified. The above information established all the objectives of this study by: showing the impacts associated with a typical cement plant, and affirming that these impacts, as seen in most of the literature, also exist in a South African cement plant, which was the objective of this study; analyzing the environmental impact of a South African cement plant using both the problem-oriented approach (midpoint) and damage-oriented approach (endpoint) of ReCiPe; and assessing and establishing the effect of these impacts on both human beings, species, resources and the environment as a whole.

5.3 Recommendations

Recommendations take the form of actions, practices and procedures needed to be taken to improve the production system. This study considered the recommendations needed to improve environmental impacts and consequently the damage caused for every 1kg of cement produced. The recommendations are made in two forms: mitigation and adaptation.

5.3.1 Mitigation

Mitigation strategies will involve improvements to procedures and practices used in the production process. This will also involve considering alternative fuels and materials used in the production process. These strategies will help reduce the damage and the impacts on both human health and the environment caused by energy sources (fossil fuels and electricity) and raw material consumption during the production of cement.

5.3.1.1 Reduction of CO_2 emission

CO_2 emission can be reduced by improving the energy efficiency of the production process as well as the units such as the kiln, cyclones etc. and/ or constructing new energy-efficient kilns. Also, the removal of CO_2 from the flue gases may contribute to a reduction in further CO_2 emission. One of the emerging technologies in this field is Post-combustion Capture. This refers to capturing carbon dioxide (CO_2) from a flue gas generated after the combustion of a carbon-based fuel, such as coal or natural gas. This captured CO_2 can then be compressed, transported and stored in that form or other geological formations. In addition, replacing high-carbon fossil fuels with low-carbon fossil fuels would reduce the CO_2 emissions although this would depend on the regional costs of the various fuels. Use of alternative fuels with low sulphur content would also reduce emissions; the co-processing of alternative fuels in cement kilns would equally reduce harmful emissions (SO_x inclusive). Co-processing involves using waste as a raw material and/or source of energy. This is a very cost-effective measure.

5.3.1.2 Use of supplementary cementing materials (SCMs)

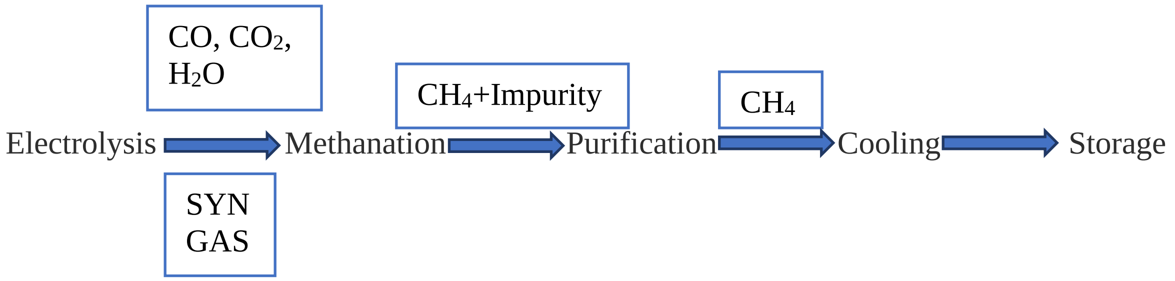
Supplementary cementing materials (SCMs) are cementitious materials that can improve the qualities of cement in one way or another. Partial replacement of limestone with some of these materials would reduce the emission of CO_2 during calcination. Also, the clinker/ cement ratio could be reduced by substituting part of the clinker with SCMs. This would produce blended cement which is still of a high quality. The production of blended cement seems to be a promising option to reduce both fuel- and process-related CO_2 emissions in the short term, while in the long term, the application of alternative cements (mineral polymers from kaolin) could be considered. A study carried out by Huntzinger in 2009 revealed that blended cement with natural pozzolans presented the highest environmental savings, closely followed by the use of cement kiln dust (CKD) for seclusion [63].

5.3.1.3 Incorporating BAT recommended by best available techniques reference document (BREF)

This process involves adopting best available techniques as prescribed by reliable sources into production processes. The Best Available Techniques Reference Document (BREF) refers to a European Union range of reference works. It was developed primarily for the exchange of information between industrial sectors and non-government organizations (NGOs) in different member states and the European Integrated Pollution Prevention and Control Bureau (IPCC/EIPPCB). It includes about 35 industrial sectors and it takes about three years to write each reference document. It was intended that each document would be revised every three years. In the study by Valderrama *et al.* on the implementation of best available techniques in cement manufacturing: a life-cycle assessment study, a plant unit was built to incorporate some of the recommendations that were presented in the BREF of 2010 [128]. This study presented the reduction of environmental impact as a result of incorporating BAT into the clinker manufacturing process. This was done by comparing the production line L6 with the previous production lines. The result of the assessment showed that incorporating BAT in the cement industry led to important environmental savings in the production process of clinker. The most impressive improvement was seen in the energy efficiency of the new kiln which consumed less fossil fuel with reduced emission when 1kg of clinker was produced. The energy demand of the unit was reduced by 17% (3035MJ/t). It is known that the grinding process consumes the highest amount of electricity in the production process of cement. BAT minimizes the high amount of electrical energy consumed by incorporating equipment with minimal electricity consumption.

5.3.2 Adaptation

Adaptation strategies would be measures taken to adapt to or live with these emissions causing damage and having an impact on both human health and the environment. A sustainable system of operation to live with these various emissions would be a close-loop system. A close-loop system, or production process, is one in which the waste and emissions from the various production processes can be used to produce the product and/ or other products. The emissions from this production system could be used as the raw material for another production system. This way, the emissions and waste have valuable reuse which translates into minimal impact. This strategy would require that waste and emissions produced from the production of cement would need to be considered for use in a production process that required this waste as the base product. A good example of this is the use of CO_2 stored from using the post- combustion capture technology to serve as a means of sustainable energy source. This process is known as power-to-gas (P2G) technology. This technology uses excess electricity (for example, electricity that is not used at night when people are asleep) to produce hydrogen through electrolysis. This hydrogen together with carbon monoxide (CO) and CO_2 forms synthesis natural gas (SYN Gas) and can be converted to methane (biomethane) through a process known as methanation.



This assists in the production of renewable fuels for industry, transportation and household use. It also helps to optimize energy production systems and to reduce energy waste. One good thing about this renewable energy source is that it doesn't require new grids; the existing natural gas grids can still be used to convey the biomethane after the upgrade (purification). Producing enough required energy is one of the problems this country is facing at the moment so this might be a good alternative to reduce the load on electricity grids by using natural gas. This process could also be applied in a beer producing company (brewery). A substantial quantity of beer is produced in SA and CO_2 is the highest emission from the process. Combining the emissions from a cement plant and a beer producing plant to produce a renewable energy source would, to a degree, increase the supply of the energy required. The abovementioned technologies and improvements would require substantial further study, research and development to ascertain the feasibility of their application, emission reduction potential and economic viability.

5.4 Future research

Further research could include strategies to reduce or eliminate the effects of emission on the population and to assess the issue of vulnerability to fully understand the potential consequences of both continuous and intermittent exposure to indoor air with both high and low CO_2 concentrations. Further research could also focus on discovering the best fit of mitigation strategies recommended in this study. Best fit implies high emission-reduction potential, effective applicability and low cost, and allows the use of existing equipment. In addition, research on sources of sustainable resource could be undertaken.

REFERENCES

[1] Constructible, "A (very) brief history of the construction industry," Trimble., Ed., ed, 2019.
[2] M. S. T. Hagos, "Historical background of the construction industry," ed, 2012.
[3] G. Nick, CMI® and K. Shepard, "The history of Concrete, ," I. c. h. i. (InterNACHI), Ed., ed, 2006.
[4] G. scientific, "The history of Concrete," ed, 2017.
[5] U. Cement, "Cement history," ed, 2014.
[6] O. M. Thomas and M. L. Frederick, "Cement," in *Encyclopedia Britannica*, ed, 2021.
[7] W. C. Association, "History of cement," ed: WCA, 2016.
[8] M. Taylor, C. Tam, and D. Gielen, "Energy efficiency and CO_2 emissions from the global cement industry," *Korea*, vol. 50, no. 2.2, p. 61.7, 2006.
[9] J. Eros and L. Candelario-Quintana, "Mineral facilities of Africa and the Middle East," *US Geological Survey Open-File Report*, vol. 1135, 2006.
[10] T. W. Bank, "Cement sectore program in Sub-Saharan Africa: barriers analysis to CDM and Solutions," Carbon finance assitance2009.
[11] Imara, "SSA Cement Industry Report," Imara investing in Africa2014, Available: https://vdocuments.net/download/imara-investing-in-africa-cement-report02-january-2014-1pdfaa-cement-production.html.
[12] Aecom, "The blue book," in "Property and Construction Handbook," 2014, Available: https://aecom.com/bh/wp-content/uploads/2019/07/Construction-Handbook-2018_update-1907-LR-2.pdf.
[13] T. Zengeni and P. Mondliwa, "Consolidation and entry: changing dynamics in the regional cement."
[14] W. Cement, "Middle Africa's cement sector: explosive growth," Ecobank2014, Available: https://www.worldcement.com/africa-middle-east/30072014/middle-africa-cement-sector-explosive-growth-205/.
[15] I. C. Review, "Global Cement Report," 2007, Available: http://www.cemnet.com/publications/GlobalCementReport/default.aspx.
[16] K. Swan, "Annual Report," ed: Central Bank of Kenya, 2006a.
[17] S. Branch, "United Nations Statistics Division," 2012.
[18] P. SA, "World Population Prospects," in *Population Division*, ed: Department of Economic and Social Affairs, 2019.
[19] Worldometer, "Population of Africa ", ed, 2020.
[20] T. Waerp, "Sub-Saharan cement," England2018.
[21] T. Abergel, J. Dulac, I. Hamilton, M. Jordan, and A. Pradeep, "Global Status Report for Buildings and Construction-towards a zero-emissions, efficient and resilient buildings and construction sector," ed: International Energy Agency, Global Alliance for Buildings and Construction, 2019.
[22] I. IEA, "World Energy Statistics and Balances, IEA," ed: OECD, Paris (France), 2019.
[23] N. A. Madlool, R. Saidur, M. S. Hossain, and N. Rahim, "A critical review on energy use and savings in the cement industries," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 4, pp. 2042-2060, 2011.
[24] C. De Gouvello, F. B. Dayo, and M. Thioye, "Low-carbon energy projects for development in Sub-Saharan Africa," *Unveiling the Potential, Addressing the Barriers*, 2008.

[25] E. Franzoni, "Materials selection for green buildings: which tools for engineers and architects?," *Procedia Engineering,* vol. 21, pp. 883-890, 2011.
[26] M. Garside, "Major countries in worldwide cement production 2015–2019," *Statista International,* 2020.
[27] L. Rodgers, "Climate change: The massive CO2 emitter you may not know about," *BBC News,* 2018.
[28] N. Madlool, R. Saidur, N. Rahim, M. Islam, and M. Hossian, "An exergy analysis for cement industries: an overview," *Renewable and Sustainable Energy Reviews,* vol. 16, no. 1, pp. 921-932, 2012.
[29] T. A. Boden, G. Marland, and R. J. Andres, "Global, regional, and national fossil-fuel CO2 emissions," *Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, Tenn., USA doi,* vol. 10, 2009.
[30] S. Mohr, J. Wang, G. Ellem, J. Ward, and D. Giurco, "Projection of world fossil fuels by country," *Fuel,* vol. 141, pp. 120-135, 2015.
[31] B. Dudley, "BP statistical review of world energy," *BP Statistical Review, London, UK, accessed Aug,* vol. 6, no. 2018, p. 00116, 2018.
[32] I. S. Organization, *ISO 14040: Environmental management-Life cycle assessment-Principles and framework*. 1997.
[33] I. O. F. Standardization, *Environmental Management: Life Cycle Assessment; Principles and Framework* (no. 2006). ISO, 2006.
[34] N. Martin, M. Levine, L. Price, and E. Worrell, "Efficient use of energy utilizing high technology: An assessment of energy use in industry and buildings," *London: World Energy Council,* 1995.
[35] E. Worrell, L. Price, N. Martin, C. Hendriks, and L. O. Meida, "Carbon dioxide emissions from the global cement industry," *Annual review of energy and the environment,* vol. 26, no. 1, pp. 303-329, 2001.
[36] P. Shukla and L. Sharma, "Improvement of Logistics and Supply Chain Management in the Cement Industry: a Literature," 2015.
[37] W. L. Greer, M. Johnson, E. Morton, E. Raught, H. Steuch, and C. Trusty Jr, "Portland Cement in Air Pollution Engineering Manual. Anthony J. Buonicore and Waynte T. Davis," ed: New York: Van Nostrand Reinhold, 1992.
[38] W. H. Duda, "International process engineering in the cement industry," *Cement-Data-Book,* vol. 1, pp. 1997.157-176, 1985.
[39] P. A. Alsop, *Cement plant operations handbook: for dry process plants*. Tradeship Publications Ltd, 2007.
[40] C. Holderbank, "Present and future energy use of energy in the cement and concrete industries in Canada," *CANMET Canada Cent Miner Energy Technol,* 1993.
[41] A. Van Kuijk, A. Schakel, and P. Vissers, "Dutch Notes on BAT for the Production of Cement Clinker," *Ministry of Housing, Spatial Planning and the Environment, The Hague, The Netherlands,* 1997.
[42] H. Von Seebach, E. Neumann, and L. Lohnherr, "State-of-the-art of energy-efficient grinding systems," *ZKG international,* vol. 49, no. 2, pp. 62-67, 1996.
[43] S. Buzzi, "Die Horomill, eine neue Mühle für die Feinzerkleinerung," *ZKG international,* vol. 50, no. 3, pp. 127-138, 1997.

[44] R. Gollop and H. Taylor, "Microstructural and microanalytical studies of sulfate attack. I. Ordinary Portland cement paste," *Cement and Concrete Research,* vol. 22, no. 6, pp. 1027-1038, 1992.

[45] R. Van Heijningen, J. de Castro, and E. Worrell, "Meer energiekentallen in relatie tot preventie en hergebruik van afvalstromen," 1992.

[46] C. Hendriks, E. Worrell, L. Price, N. Martin, and L. O. Meida, "The reduction of greenhouse gas emissions from the cement industry," *IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom (Report PH3/7), May,* 1999.

[47] R. M. Andrew, "Global CO_2 emissions from cement production," *Earth System Science Data,* vol. 10, no. 1, p. 195, 2018.

[48] R. M. Andrew, "Global CO_2 emissions from cement production, 1928–2017," *Earth System Science Data,* vol. 10, no. 4, pp. 2213-2239, 2018.

[49] S. Morsali, "Emissions from portland cement production using life cycle assessment inventory and method," *Environ Energy Econ,* vol. 1, no. 1, pp. 1-8, 2016.

[50] S.-H. Cho and C.-U. Chae, "The comparative study on the environmental impact assessment of construction material through the application of carbon reducing element-focused on global warming potential of concrete products," *KIEAE Journal,* vol. 15, no. 1, pp. 147-154, 2015.

[51] S.-H. Cho and C.-U. Chae, "A study on life cycle CO_2 emissions of low-carbon building in South Korea," *Sustainability,* vol. 8, no. 6, p. 579, 2016.

[52] Y. Weon, "A study of life-cycle energy consumption and basic unit of CO_2 emission of prototype office building," *The Graduate School of Kwangwoon University, Seoul, the Republic of Korea,* pp. 87-91, 2013.

[53] F. N. Stafford, F. Raupp-Pereira, J. A. Labrincha, and D. Hotza, "Life cycle assessment of the production of cement: A Brazilian case study," *Journal of Cleaner Production,* vol. 137, pp. 1293-1299, 2016.

[54] R. Muigai, M. Alexander, and P. Moyo, "Cradle-to-gate environmental impacts of the concrete industry in South Africa," *Journal of the South African Institution of Civil Engineering= Joernaal van die Suid-Afrikaanse Instituut van Siviele Ingenieurswese,* vol. 56, no. 1, p. 108, 2014.

[55] B. Pré Consultants, "SimaPro," *URL: https://network. simapro. com/esuservices,* 2016.

[56] L. Moretti and S. Caro, "Critical analysis of the life cycle assessment of the Italian cement industry," *Journal of Cleaner Production,* vol. 152, pp. 198-210, 2017.

[57] D. A. Salas, A. D. Ramirez, C. R. Rodriguez, D. M. Petroche, A. J. Boero, and J. Duque-Rivera, "Environmental impacts, life cycle assessment and potential improvement measures for cement production: a literature review," *Journal of Cleaner Production,* vol. 113, pp. 114-122, 2016.

[58] D. García-Gusano, D. Garraín, I. Herrera, H. Cabal, and Y. Lechón, "Life Cycle Assessment of applying CO_2 post-combustion capture to the Spanish cement production," *Journal of Cleaner Production,* vol. 104, pp. 328-338, 2015.

[59] M. E. Boesch and S. Hellweg, "Identifying improvement potentials in cement production with life cycle assessment," *Environmental science & technology,* vol. 44, no. 23, pp. 9143-9149, 2010.

[60] S. P. Holt and N. D. Berge, "Life-cycle assessment of using liquid hazardous waste as an alternative energy source during Portland cement manufacturing: A United States case study," *Journal of Cleaner Production,* vol. 195, pp. 1057-1068, 2018.

[61] F. N. Stafford, A. C. Dias, L. Arroja, J. A. Labrincha, and D. Hotza, "Life cycle assessment of the production of Portland cement: a Southern Europe case study," *Journal of cleaner production,* vol. 126, pp. 159-165, 2016.
[62] R. Feiz, J. Ammenberg, L. Baas, M. Eklund, A. Helgstrand, and R. Marshall, "Improving the CO2 performance of cement, part I: utilizing life-cycle assessment and key performance indicators to assess development within the cement industry," *Journal of Cleaner Production,* vol. 98, pp. 272-281, 2015.
[63] D. N. Huntzinger and T. D. Eatmon, "A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies," *Journal of Cleaner Production,* vol. 17, no. 7, pp. 668-675, 2009.
[64] E. BREF, "Draft Reference Document on Best Available Techniques in the Cement, Lime and Magnesium Oxide Manufacturing Industries (2009)," ed, 2009.
[65] F. Schorcht, I. Kourti, B. M. Scalet, S. Roudier, and L. D. Sancho, "Best available techniques (BAT) reference document for the production of cement, lime and magnesium oxide," *European Commission Joint Research Centre Institute for Prospective Technological Studies, Luxembourg,* 2013.
[66] M. Schneider, M. Romer, M. Tschudin, and H. Bolio, "Sustainable cement production—present and future," *Cement and concrete research,* vol. 41, no. 7, pp. 642-650, 2011.
[67] C. Ouellet-Plamondon and G. Habert, "Life cycle assessment (LCA) of alkali-activated cements and concretes," in *Handbook of alkali-activated cements, mortars and concretes*: Elsevier, 2015, pp. 663-686.
[68] S. H. Teh, T. Wiedmann, A. Castel, and J. de Burgh, "Hybrid life cycle assessment of greenhouse gas emissions from cement, concrete and geopolymer concrete in Australia," *Journal of Cleaner Production,* vol. 152, pp. 312-320, 2017.
[69] M. Georgiopoulou and G. Lyberatos, "Life cycle assessment of the use of alternative fuels in cement kilns: A case study," *Journal of environmental management,* vol. 216, pp. 224-234, 2018.
[70] S. Çankaya and B. Pekey, "A comparative life cycle assessment for sustainable cement production in Turkey," *Journal of environmental management,* vol. 249, p. 109362, 2019.
[71] M. Ormazabal, C. Jaca, and R. Puga-Leal, "Analysis and Comparison of Life Cycle Assessment and Carbon Footprint Software," in *Proceedings of the Eighth International Conference on Management Science and Engineering Management*, 2014, pp. 1521-1530: Springer.
[72] M. Huijbregts, "Uncertainty and variability in environmental life-cycle assessment," *The International Journal of Life Cycle Assessment,* vol. 7, no. 3, pp. 173-173, 2002.
[73] J. Guinée *et al.*, "Life Cycle Assessment—An Operational Guide to the ISO Standards Ministry of Housing," *Spatial Planning and the Environment (VROM), and Centre of Environmental Science, Leiden University (CML), The Netherlands,* 2001.
[74] M. Goedkoop, S. Effting, and M. Collignon, *The eco-indicator 99: a damage oriented method for life-cycle impact assessment: manual for designers*. PRé Consultants, 2000.
[75] S. B. Young, S. Turnbull, and A. Russell, "Substudy 6: What LCA Can Tell Us about the Cement Industry," 2002.
[76] T. Gloria, "LCA Software," ed: Life Cycle Assessment Links, 2000.
[77] N. De Caluwe, "Ecotools manual—a comprehensive review of design for environment tools," *Design for the Environment Research Group, Manchester Metropolitan University Manchester, UK*, 1997.

[78] A. K. Jönbrink, C. Wolf-Watz, M. Erixon, P. Olsson, and E. Wallén, *LCA software survey*. IVL Svenska Miljöinstitutet, 2000.
[79] M. Goedkoop, M. Oele, J. Leijting, T. Ponsioen, and E. Meijer, "Introduction to LCA with SimaPro (v 5.2)," *PRé Consultants: Amersfoort, The Netherlands,* 2016.
[80] T. Kupfer *et al.*, "GaBi Database & Modelling Principles," 2017.
[81] A. Ciroth, C. Di Noi, T. Lohse, and M. Srocka, "OpenLCA 1.9 Comprehensive User Manual," ed: GreenDelta GmbH: Berlin, Germany, 2019.
[82] I. H. GmbH, " User Manual. 3.55 ed," *GmbH 258.,* vol. Umberto® LCA+(v10), 2017.
[83] OPENLCA. Available: https://www.openlca.org/project/modeling-compliant-to-standards/
[84] J. I. Kreissig, "University of Stuttgart, Germany. Personal Communication," 2001.
[85] F. Ailleret, "Comparison of energy systems using life cycle assessment," *World Energy Council, London, UK,* vol. 2, no. 1, p. 3.1, 2004.
[86] S. You and X. Wang, "On the Carbon Abatement Potential and Economic Viability of Biochar Production Systems: Cost-Benefit and Life Cycle Assessment," in *Biochar from Biomass and Waste*: Elsevier, 2019, pp. 385-408.
[87] S. M. El Haggar, "Rural and developing country solutions," in *Environmental Solutions*: Elsevier, 2005, pp. 313-400.
[88] S. Hellweg and L. M. i Canals, "Emerging approaches, challenges and opportunities in life cycle assessment," *Science,* vol. 344, no. 6188, pp. 1109-1113, 2014.
[89] L. HOFFMAN and A. Schmidt, "Life Cycle Assessment. A guide to approaches, experiences and information sources," *recurso electronic, EPA,* 1997.
[90] S. Marinković, "Life cycle assessment (LCA) aspects of concrete," in *Eco-Efficient Concrete*: Elsevier, 2013, pp. 45-80.
[91] S. Marinković, J. Dragaš, I. Ignjatović, and N. Tošić, "Environmental assessment of green concretes for structural use," *Journal of Cleaner Production,* vol. 154, pp. 633-649, 2017.
[92] G. Kabir, A. Abubakar, and U. El-Nafaty, "Energy audit and conservation opportunities for pyroprocessing unit of a typical dry process cement plant," *Energy,* vol. 35, no. 3, pp. 1237-1243, 2010.
[93] K. Andersson, T. Ohlsson, and P. Olsson, "Life cycle assessment (LCA) of food products and production systems," *Trends in Food Science & Technology,* vol. 5, no. 5, pp. 134-138, 1994.
[94] G. Tansey, T. Worsley, and B. Traill, "The food system," *Nature,* vol. 378, no. 6552, pp. 102-102, 1995.
[95] I. S. Arvanitoyannis, "ISO 14040: life cycle assessment (LCA)–principles and guidelines," *Waste management for the food industries,* pp. 97-132, 2008.
[96] T. Tibor and I. Feldman, *Implementing ISO 14000: a practical, comprehensive guide to the ISO 14000 environmental management standards*. Irwin Professional Pub, 1997.
[97] O. Edenhofer *et al.*, *Renewable energy sources and climate change mitigation: Special report of the intergovernmental panel on climate change*. Cambridge University Press, 2011.
[98] L. Barcelo, J. Kline, G. Walenta, and E. Gartner, "Cement and carbon emissions," *Materials and Structures,* vol. 47, no. 6, pp. 1055-1065, 2014.
[99] J. M. Allwood *et al.*, *Sustainable materials: with both eyes open*. Citeseer, 2012.
[100] M. Ali, R. Saidur, and M. Hossain, "A review on emission analysis in cement industries," *Renewable and Sustainable Energy Reviews,* vol. 15, no. 5, pp. 2252-2261, 2011.

[101] M. Fry, "Cement, carbon dioxide, and the 'necessity'narrative: A case study of Mexico," *Geoforum,* vol. 49, pp. 127-138, 2013.
[102] A. P. Gursel, "Life-cycle assessment of concrete: decision-support tool and case study application," UC Berkeley, 2014.
[103] U. S. E. P. Agency, *Inventory of US Greenhouse Gas Emissions and Sinks: 1990-1997* (Office of Policy). The Agency, 1999.
[104] M. Goedkoop, R. Heijungs, M. Huijbregts, A. De Schryver, J. Struijs, and R. Van Zelm, "ReCiPe 2008," *A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level,* vol. 1, pp. 1-126, 2009.
[105] F. Pacheco-Torgal, L. F. Cabeza, J. Labrincha, and A. G. De Magalhaes, *Eco-efficient construction and building materials: life cycle assessment (LCA), eco-labelling and case studies*. woodhead Publishing, 2014.
[106] L. P. Güereca, N. Torres, and C. R. Juárez-López, "The co-processing of municipal waste in a cement kiln in Mexico. A life-cycle assessment approach," *Journal of Cleaner Production,* vol. 107, pp. 741-748, 2015.
[107] G. R. A. D. Services, "Cement Market in South Africa to 2019 – Market Size, Development and Forecasts. ," 2015.
[108] M. A. Emeran, "South Africa's cement industry is settling firmly.," 2016.
[109] Anonymous. PPC, "PPC Integrated Report 2014," 2014.
[110] W. S. Africa, "Constructing a case for geopolymer cement," 2017.
[111] Anonymous. ACM Producers, "Cementing a Sustainable Future, 2008-2011," 2011.
[112] Anonymous. DEA, "GHG National Inventory Report, South Africa 2000-2010.," 2014, Available: http://www.saaqis.org.za.
[113] T. L. Rachel Muigai, Emilia Moreno Ruiz, Marion Sié, Sié, "Ecoinvent 3.6 dataset documentation Cement production, Portland - ZA," E. Association, Ed., 3.6 - Allocation, cut-off ed. Identifying Improvement Potentials in Cement Production with Life Cycle Assessment 2010, 2019.
[114] M. S. Rachel Muigai, Sié, Emilia Moreno Ruiz, Tereza Levova, "Ecoinvent 3.6 dataset documentation clinker production - (South Africa) ZA," E. Association, Ed., 3.6 - Allocation, cut-off ed. Life Cycle Inventories of Cement, Concrete and Related Industries - South Africa 2017, 2019.
[115] T. L. Milfont, "Global warming, climate change and human psychology," *Psychological approaches to sustainability: Current trends in theory, research and practice,* vol. 19, p. 42, 2010.
[116] K. Pawlik, "The psychology of global environmental change: Some basic data and an agenda for cooperative international research," *International journal of psychology,* vol. 26, no. 5, pp. 547-563, 1991.
[117] N. Goel, "Design mix concrete- Economy & Environmental isuues," ed. N. Delhi: Central Vigilance Commission, 2011.
[118] CivilRnD, "M20 Grade Concrete Mix Design – IS10262 Latest Edition," ed: Research and Development., 2021.
[119] M. Nataraja and L. Das, "Concrete mix proportioning as per IS 10262: 2009–Comparison with IS 10262: 1982 and ACI 211.1-91," *The Indian Concrete Journal,* pp. 64-70, 2010.
[120] C. R. Gagg, "Cement and concrete as an engineering material: An historic appraisal and case study analysis," *Engineering Failure Analysis,* vol. 40, pp. 114-140, 2014.

[121] A. Martínez-Rocamora, J. Solís-Guzmán, and M. Marrero, "LCA databases focused on construction materials: A review," *Renewable and Sustainable Energy Reviews,* vol. 58, pp. 565-573, 2016.
[122] C. Meyer, "The greening of the concrete industry," *Cement and concrete composites,* vol. 31, no. 8, pp. 601-605, 2009.
[123] T. A. Jacobson, J. S. Kler, M. T. Hernke, R. K. Braun, K. C. Meyer, and W. E. Funk, "Direct human health risks of increased atmospheric carbon dioxide," *Nature Sustainability*, vol. 2, no. 8, pp. 691-701, 2019.
[124] N. Geoscience, "The great climate conundrum," *Nature Geoscience*, vol. 12, no. 8, pp. 581-581, 2019/08/01 2019.
[125] S. Singh, "Is nuclear energy the deadliest of them all?," in *Business Standard*, ed, 2015.
[126] Worldometer, "South Africa Population (LIVE)," ed, 2021.
[127] C. Li, S. Cui, Z. Nie, X. Gong, Z. Wang, and N. Itsubo, "The LCA of Portland cement production in China," *The International Journal of Life Cycle Assessment*, vol. 20, no. 1, pp. 117-127, 2015.
[128] C. Valderrama, R. Granados, J. L. Cortina, C. M. Gasol, M. Guillem, and A. Josa, "Implementation of best available techniques in cement manufacturing: a life-cycle assessment study," *Journal of Cleaner Production*, vol. 25, pp. 60-67, 2012.

APPENDIX 1

Ecoinvent 3.6 database documentation of clinker production: South Africa (ZA)

Process description

This activity represents the production of clinker which is a component of Portland cement. The Association of Cementitious Material Producers (ACMP) in South Africa described the clinker manufacturing process as one requiring the use of calcareous deposits, such as limestone, marl or chalk to provide calcium carbonate ($CaCO_3$), and very small amounts of "corrective" materials such as iron ore, bauxite, shale, clay or sand, which may be needed to provide extra iron oxide (Fe_2O_3), alumina (Al_2O_3) and silica (SiO_2) to achieve the desired chemical composition of the raw mix. The raw materials are quarried and transported to the primary/secondary crushers located at the cement plants via trucks, train or conveyor belts and broken into material particles that are smaller than 19mm in diameter. The material is then conveyed from the crusher to the stockpile, where it is stored before going to the raw mill. All South African cement plants make use of a dry process raw milling process. In the raw mill, prehomogenization takes place in which different raw materials are mixed to obtain the required chemical composition, and the crushed pieces are then milled together to produce "raw meal". After the raw milling process, the coarse particles are separated from the fine particles and sent back to the raw mill. The fine particles are transported to the raw meal silos by means of fans or compressed air. The raw meal is then preheated and pre-calcined where 60% - 80% of the calcination takes place before it enters the kiln, where it is heated to temperatures of up to 1450^{o}C. The intense heat causes chemical and physical reactions that partially melt the meal into clinker. From the kiln, the hot clinker falls into a grate cooler where it is cooled by incoming combustion air. Clinker is stored before grinding, which is a necessary step in order for it to be ready for cement production.

Dataset description

This dataset is based on primary data collection from one cement company in ZA representing 15% of the market share for raw materials and energy consumption. Several other data sources were used to elaborate this dataset. These are:

Energy inputs

(1) There is a lack of documentation on the energy used due to co-processing/ secondary fuel usage in local cement companies. Secondary fuel sources such as tyres and waste sludge are currently being used on a trial basis.

(2) Primary data collection is from one cement company representing 15% of the cement market share in South Africa.

(3) Eskom (2011). "Concrete steps towards profitability: Solid ways to ensure energy effici ent cement production", Cement brochure, Available at: http://www.eskom.co.za/sites/idm/Documents/128251_Cement_Brochure.pdflarger.

For emissions to air:

(1) Karstensen, K.H., (2007). National policy on high temperature thermal waste treatment and cement kiln alternative fuel use. In: Thermal waste treatment and cement kiln alternative fuel use. Department of Environmental Affairs and Tourism, South Africa.

(2) Extrapolated values from “clinker production, GLO 2003” dataset.

This dataset has been extrapolated from the year 2017 to the year of the calculation (2019). The uncertainty has been adjusted accordingly. Typical technology for South African production (including Long dry and pre-calciner kilns) represents South Africa’s cement mills. Some of the data has been extrapolated from GLO clinker production datasets. The production volume provided represents the average production volume in 2008. The uncertainty of the 2008 inventory data provided has been adjusted accordingly. The uncertainty distribution adopted all through this dataset is lognormal.

Table 1: All technical input and output data

Reference product	Amount
Clinker	1 kg
Inputs from Technosphere	Amount

Ammonia, liquid	0.000918 kg
Bauxite	0.04 kg
Cement factory	6.2e-12 unit
Diesel, burned in building machine	0.0132 MJ
Diesel, low-sulphur	0.000427 kg
Electricity, medium voltage	0.14 kWh
Hard coal	0.145 kg
Industrial machine, heavy, unspecified	3.76e-05 kg
Iron ore, crude ore, 46% Fe	0.000143 kg
Light fuel oil	0.000367 kg
Lime, hydrated, loose weight	0.00388 kg
Limestone, crushed, for mill	0.9 kg
Lubricating oil	4.71e-05 kg
Magnetite	0.01 kg
Refractory, basic, packed	0.00019 kg
Refractory, fireclay, packed	8.21e-05 kg
Refractory, high aluminum oxide, packed	0.000137 kg
Sand	0.05 kg
Steel, chromium steel 18/8, hot rolled	5.86e-05 kg
Inputs from Technosphere	**Amount**
Tap water	0.336 kg
Urea, as N	1.5e-06 kg
Inputs from environment	**Amount**
Water, cooling, unspecified natural origin	9.57e-06 m3
Water, unspecified natural origin	0.0016 m3
Emissions to air	**Amount**
Ammonia	2.25e-05 kg
Antimony	2.24e-09 kg
Arsenic	1.22e-08 kg
Beryllium	2.97e-09 kg
Cadmium	6.87e-09 kg
Carbon dioxide, fossil	0.838 kg
Carbon dioxide, non-fossil	0.0155 kg
Carbon monoxide, fossil	0.000489 kg
Chromium	2.1e-09 kg
Chromium VI	5.44e-10 kg
Cobalt	3.98e-09 kg
Copper	1.42e-08 kg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	9.43e-13 kg
Lead	8.39e-08 kg
Manganese	5.74e-10 kg

Mercury	3.25e-08 kg
Methane, fossil	8.79e-06 kg
NMVOC, non-methane volatile organic compounds	5.59e-05 kg
Nickel	6.71e-09 kg
Nitrogen oxides	0.000977 kg
Particulates, < 2.5 um	2.37e-05 kg
Particulates, > 10 um	6.5e-06 kg
Particulates, > 2.5 um, and < 10um	0.000123 kg
Selenium	1.98e-09 kg
Sulphur dioxide	5.92e-05 kg
Thallium	1.3e-08 kg
Tin	9.05e-09 kg
Vanadium	4.97e-09 kg
Water	0.000294 m3
Zinc	6.34e-08 kg
Emissions to air	**Amount**
Ammonia	2.25e-05 kg
Antimony	2.24e-09 kg
Arsenic	1.22e-08 kg
Beryllium	2.97e-09 kg
Cadmium	6.87e-09 kg
Carbon dioxide, fossil	0.838 kg
Carbon dioxide, non-fossil	0.0155 kg
Carbon monoxide, fossil	0.000489 kg
Chromium	2.1e-09 kg
Chromium VI	5.44e-10 kg
Cobalt	3.98e-09 kg
Copper	1.42e-08 kg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	9.43e-13 kg
Lead	8.39e-08 kg
Manganese	5.74e-10 kg
Mercury	3.25e-08 kg
Methane, fossil	8.79e-06 kg
NMVOC, non-methane volatile organic compounds, unspecified origin	5.59e-05 kg

Detailed information for exchanges

Reference product	Annual production volume.	Amount
Clinker	1.27e+10 kg	1 kg

Annual production capacity of 90% of cement mills in South Africa in 2008. Source:

C&CI; (2008). Cement and Concrete Institute South Africa, "Cement and Concrete Review (annual)". Carbon Disclosure Project (2012).

Inputs from Technosphere: Material/Fuel/Electricity/heat	Amount
1) Ammonia, liquid	0.000918 kg

Ancillary material for nitrogen oxide removal during burning process. This an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset.

2) Bauxite	0.04 kg

Raw material for clinker production. Primary data collected from one cement company in SA representing 15% of the market share.

3) Cement factory	6.2e-12

Ancillary product for grinding. This an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset.

4) Diesel, burned in building machine	0.0132 MJ

This an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset. Calculated as a weighted average (by production volume) of the regional activities.

5) Diesel low-sulphur	0.000427 kg

Diesel fuel. Primary data collected from one cement company in SA representing 15% of the market share.

6) Electricity, medium voltage	0.14 kWh

Energy for operation (conveyors, grinding, etc.), primary data collected from one cement company in SA representing 15% of the market share. Secondary data source: Eskom (2011). "Concrete steps towards profitability: Solid ways to ensure energy efficient cement production", Cement brochure, Available at: http://www.eskom.co.za/sites/idm/Documents/ 128251_Cement_Brochure.pdflarger

7) Hard coal	0.145 kg

Kiln fuel-cement kilns in South Africa utilize coal and oil sludge. Primary data collected from one cement company in SA representing 15% of the market share.

8) Industrial machine, heavy, unspecified	3.76e-05 kg

Kiln infrastructure. This is an extrapolated value. It was adapted from the "clinker production, GLO 2003" dataset.

9) Iron ore, crude ore, 46% Fe	0.000143 kg

Raw material for clinker production. This value was derived from literature. Original data given per ton of cement.

10) Light fuel oil	0.000367 kg

Adapted from the "clinker production, GLO 2003" dataset.

11) Lime, hydrated, loose weight	0.00388 kg

This an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset. Calculated as a weighted average (by production volume) of the regional activities.

12) Limestone, crushed, for mill	0.9 kg

Primary data collected from one cement company in SA representing 15% of the market share.

13) Lubricating oil	4.71e-05 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset. Calculated as a weighted average (by production volume) of the regional activities.

14) Magnetite	0.01 kg

Primary data collected from one cement company in SA representing 15% of the market share.

15) Refractory, basic, packed	8.21e-05 kg

Process material (wearing parts in the cement kiln). This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset.

16) Refractory, fireclay, packed	8.21e-05 kg

Process material (wearing parts in the cement kiln). This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset.

17) Refractory, high aluminum oxide, packed	0.000137 kg

Process material (wearing parts in the cement kiln). This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset.

18) Sand	0.05 kg

Primary data collected from one cement company in SA representing 15% of the market share.

19) Steel, chromium steel 18/8, hot rolled	5.86e-05 kg

Ancillary product for grinding (wearing parts). This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset.

20) Tap water	0.336 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset. Calculated as a weighted average (by production volume) of the regional activities.

21) Urea, as N	1.5e-06 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset. Calculated as a weighted average (by production volume) of the regional activities.

Inputs from environment	**Sub-compartment**	**Amount**
1) Water, cooling, unspecified natural origin	in water	9.57e-06 m^3

Calculated value.

2)Water, unspecified natural origin	in water	0.0016 m^3

Calculated value.

Emissions to air	Sub-compartment	Amount
1) Ammonia	unspecified	2.25e-05 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset.

3) Antimony	unspecified	2.24e-09 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset.

4) Arsenic	unspecified	1.22e-08 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset.

5) Beryllium	unspecified	2.97e-09 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset.

6) Cadmium	unspecified	6.87e-09 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset

7) Carbon dioxide, fossil	unspecified	0.838 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset.

8) Carbon dioxide, non-fossil	unspecified	0.0155 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset.

9) Carbon monoxide, fossil	unspecified	0.000489 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset.

10) Chromium	unspecified	2.1e-09 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset.

11) Chromium VI	unspecified	5.44e-10 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset.

12) Cobalt	unspecified	3.98e-09 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset.

13) Copper	unspecified	1.42e-08 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset. Accessed 2017/11/07.

14) Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	unspecified	9.43e-13 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset.

15) Lead	unspecified	8.39e-08 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset.

16) Manganese	unspecified	5.74e-10 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset. Calculated as a weighted average (by production volume) of the regional activities.

17) Mercury	unspecified	3.25e-08 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset.

18) Methane, fossil	unspecified	8.79e-06 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset.

19) NMVOC, non-methane volatile organic compounds, unspecified origin	unspecified	5.59e-05 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset.

20) Nickel	unspecified	6.71e-09 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset.

21) Nitrogen oxides	unspecified	0.000977 kg

Calculated value representing an average of 20 cement kilns in ZA. Source: Karstensen, K.H., (2007). National policy on high temperature thermal waste treatment and cement kiln alternative fuel use. In: Thermal waste treatment and cement kiln alternative fuel use. Department of Environmental Affairs and Tourism, South Africa.

22) Particulates, < 2.5 um	non-urban air or from high stacks	2.37e-05 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset.

23) Particulates, > 10 um	non-urban air or from high stacks	6.5e-06 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset.

24) Particulates, > 2.5 um, and < 10um	non-urban air or from high stacks	0.000123 kg

Calculated value representing an average of 20 cement kilns in ZA. K.H., (2007). National policy on high temperature thermal waste treatment and cement kiln alternative fuel use. In: Thermal waste treatment and cement kiln alternative fuel use. Department of Environmental Affairs and Tourism, South Africa.

25) Selenium	unspecified	1.98e-09 kg

This is an extrapolated value. Adopted from the "clinker production, GLO 2003" dataset.

26) Sulphur dioxide	unspecified	5.92e-05 kg

Calculated value representing an average of 20 cement kilns in ZA. Source Karstensen, K.H. (2007). National policy on high temperature thermal waste treatment and cement kiln alternative fuel use. In: Thermal waste treatment and cement kiln alternative fuel use. Department of Environmental Affairs and Tourism, South Africa.

Source: Karstensen, K.H. 2007

27) Thallium	unspecified	1.3e-08 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset.

Emissions to air	Sub-compartment	Amount
28) Tin	unspecified	9.05e-09 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset.

29) Vanadium	unspecified	4.97e-09 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset.

30) Water	unspecified	0.000294 m^3

Calculated value

31) Zinc	unspecified	6.34e-08 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset.

Emissions to water	Sub-compartment	Amount

1) Arsenic, ion	unspecified	1.29e-10 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset. Calculated as a weighted average (by production volume) of the regional activities.

2) Cadmium, ion	unspecified	2.59e-11 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset. Calculated as a weighted average (by production volume) of the regional activities.

3) Chromium, ion	unspecified	5.18e-11 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset. Calculated as a weighted average (by production volume) of the regional activities.

4) Copper, ion	unspecified	2.59e-11 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset. Calculated as a weighted average (by production volume) of the regional activities.

5) Lead	unspecified	2.72e-11 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset. Calculated as a weighted average (by production volume) of the regional activities.

6) Mercury	unspecified	2.72e-13 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset. Calculated as a weighted average (by production volume) of the regional activities.

7) Nickel, ion	unspecified	2.59e-11 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset. Calculated as a weighted average (by production volume) of the regional activities.

8) Water	unspecified	0.00165 m^3

Calculated value

9) Zinc, ion	unspecified	5.18e-11 kg

This is an extrapolated value. It was adopted from the "clinker production, GLO 2003" dataset. Calculated as a weighted average (by production volume) of the regional activities.

Dataset authorship

Role	Name, organisation
Data generator	Rachel Muigai, University of Johannesburg
Data entry	Rachel Muigai, University of Johannesburg
Review	Marion Sié, Sié
Review	Emilia Moreno Ruiz, Ecoinvent Centre
Review	Tereza Levova, Ecoinvent Centre

Source information

First author: Karstensen, K.H.

Additional author(s): Department of Environmental Affairs and Tourism, South Africa

Title: National policy on high temperature thermal waste treatment and cement kiln alternative fuel use. In: Thermal waste treatment and cement kiln alternative fuel use.

Year: 2007

First author: Frischknecht, R.

Additional author(s): Althaus, H.J., Doka, G., Dones, R., Hellweg, S., Hischier, R., Jungbluth, N., Nemecek, T., Rebitzer, G., and Spielmann, M.

Title: Overview and Methodology

Year: 2007

Volume number: 1

First author: ESKOM

Title: Concrete steps towards profitability: Solid ways to ensure energy-efficient cement production

Year: 2011

First author: Portland Cement Association

Title: US & Canadian Labor-Energy Input Survey 2007

Year: 2008

First author: Muigai, R.

Additional author(s): Pradhan, A.

Title: Life Cycle Inventories of Cement, Concrete and Related Industries - South Africa
Year: 2017

APPENDIX 2

Ecoinvent 3.6 dataset documentation for Portland cement production: South Africa

Dataset description

The dataset describes the production of Portland cement (CEM I) and covers some relevant process steps. Portland cement production involves the chemical transformation of raw materials: calcium oxides, silica, alumina and iron oxide into various types of cementitious products, by-products and wastes. The Portland cement manufacturing process consists of four main steps:

(1) Quarrying of limestone and transportation of raw materials to the processing plant.

(2) Preparation of "raw meal" for pyro-processing

(3) Pyro-processing of raw materials to produce Portland cement clinker using the dry process.

(4) Final grinding of the clinker together with inter-grinding with a small proportion of gypsum to produce Portland cement.

Only step 4 is considered in this dataset. This is because clinker is produced and stored separately and all information can be found in Appendix 1.

This activity starts with upstream activities (putting raw materials together) and ends with the cement produced in the cement mill. The dataset does not include packaging and administration. This dataset approximates average South African production. The dataset not available has been extrapolated from year 2017 to the year of the calculation 2019. The uncertainty has been adjusted accordingly.

In South Africa, all cement production is through the dry kiln process. The clinker is ground in mills together with gypsum (5%) and depending on the type of cement and technical standard (SAN 50197-1), with other materials such as blast furnace slag, fly ash, pozzolan and lime fillers to produce Portland cement.

Table1: input and output data

Reference product	Amount
Cement, Portland	1 kg
Inputs from Technosphere	Amount
Cement factory	5.36e-11 unit
Clinker	0.902 kg
Electricity, medium voltage	0.0376 kWh
Ethylene glycol	0.00019 kg
Gypsum, mineral	0.0475 kg
Limestone, crushed, for mill	0.05 kg
Steel, low-alloyed	5.25e-05 kg
Emissions to air	Amount
Heat, waste	0.135 MJ

Detailed information of dataset values

Reference product	Annual production volume.	Amount
Cement, Portland	3.48e+9 kg	1 kg

Values were calculated based on primary data collection in South Africa. The data were collected from five cement companies, which represent 90% of the cement market share. Annual production capacity of 90% of cement mills in South Africa in 2008. Source: C&CI (2008). Cement and Concrete Institute South Africa, "Cement and Concrete Review (annual)". Carbon Disclosure Project (2012). Available at: http://www.nbi.org.za/Publications/Fastfacts/Pages/default.aspx

Source: Concrete Institute 2009

Inputs from Technosphere	Amount

1) Cement factory	5.36e-11

This is a Literature Value. It was adopted from the "Cement production, Portland, GLO 2009" dataset. With respect to uncertainty analysis, variance of log-transformed data was taken from ecoinvent report no 1, table 10.3. Value represents demand of infrastructure for input/output.

2) Clinker	0.902 kg

The values were calculated based on primary data collection in South Africa. The data were collected from five cement companies, which represent 90% of the cement market share.

3) Electricity, medium voltage	0.0376 kWh

This is a Literature Value. It was adopted from the "Cement production, Portland, GLO 2009" dataset.

4) Ethylene glycol	0.00019 kg

Ancillary product for grinding. Adopted from the "Cement production, Portland, GLO 2009" dataset.

Source: Boesch, M.E. 2010

5) Gypsum, mineral	0.0475 kg

Values were calculated based on primary data collection in South Africa. The data were collected from five cement companies, which represent 90% of the cement market share.

Source: Kellenberger, D. 2007

6) Limestone, crushed, for mill	0.05 kg

Values were calculated based on primary data collection in South Africa. The data were collected from five cement companies, which represent 90% of the cement market share.

Source: Theodosiou, Gary. 2010

7) Steel, low-alloyed	5.25e-05 kg

This is a L**i**terature Value. It was adopted from the "Cement production, Portland, CH 2010" dataset.

Source: Kellenberger, D. 2007

Emissions to air	Sub-compartment	Amount
Heat, waste	unspecified	0.135 MJ

This is a L**i**terature Value. It was adopted from the "Cement production, Portland, GLO 2009" dataset.

Source: Boesch, M.E. 2010

Dataset authorship

Role	Name, organization

Data generator	Rachel Muigai, University of Johannesburg
Data entry	Rachel Muigai, University of Johannesburg
Review	Tereza Levova, Ecoinvent Centre
Review	Emilia Moreno Ruiz, Eecoinvent Centre
Review	Marion Sié, Sié

Source information

First author: Kellenberger, D.

Additional author(s): Althaus, H.-J., Jungbluth, N., Künniger, T.

Title: Life Cycle Inventories of Building Products

Year: 2007

Volume number: 7

First author: Concrete Institute

Title: Cement and Concrete Institute South Africa

Year: 2009

First author: Theodosiou, Gary

Title: Cement and Concrete Institute Concrete Industry Greenhouse Gas Emissions

Year: 2010

First author: Boesch, M.E.

Additional author(s): Hellweg, S.

Title: Identifying Improvement Potentials in Cement Production with Life Cycle Assessment

Year: 2010

Journal: Environmental Science & Technology

Volume number: 44

Issue number: 23

First author: Muigai, R.

Additional author(s): Pradhan, A.

Title: Life Cycle Inventories of Cement, Concrete and Related Industries - South Africa

Year: 2017

APPENDIX 3

Table 1: Uncertainty results for mid-point analysis

Impact category	Unit	Mean	Median	SD	CV	2.50%	97.50%	SEM
Fine particulate matter formation	kg PM2.5 eq	0.000803	0.000737	0.000325	40.5%	0.000355	0.001615	1.03E-05
Fossil resource scarcity	kg oil eq	0.141404	0.12733	0.062775	44.34%	0.05776	0.300724	0.001985
Freshwater ecotoxicity	kg 1,4-DCB	0.016241	0.013214	0.011798	72.6%	0.005574	0.04833	0.000373
Freshwater eutrophication	kg P eq	0.000329	0.000243	0.0003	91.2%	6.02E-05	0.001051	9.48E-06
Global warming	kg CO2 eq	1.00863	0.913186	0.459852	45.6%	0.388636	2.158094	0.014542
Human carcinogenic toxicity	kg 1,4-DCB	0.026046	0.012594	0.06141	235.8%	0.003659	0.12182	0.001942
Human non-carcinogenic toxicity	kg 1,4-DCB	0.494297	0.358147	0.439479	88.9%	0.120207	1.767484	0.013898
Ionizing radiation	kBq Co-60 eq	0.0104	0.005285	0.024081	231.6	0.001014	0.050712	0.000762
Land use	m2a crop eq	0.00797	0.007082	0.003759	47.2%	0.003102	0.01781	0.000119
Marine ecotoxicity	kg 1,4-DCB	0.022008	0.017491	0.016481	74.9%	0.007482	0.067542	0.000521
Marine eutrophication	kg N eq	1.95E-05	1.75E-05	9.64E-06	49.4%	7.25E-06	4.38E-05	3.05E-07
Mineral resource scarcity	kg Cu eq	0.002204	0.002005	0.00093	42.2%	0.000926	0.004503	2.94E-05
Ozone formation, Human health	kg NOx eq	0.002116	0.001942	0.000937	44.3%	0.000851	0.004525	2.96E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.002132	0.001959	0.000945	44.3%	0.000857	0.00456	2.99E-05
Stratospheric ozone depletion	kg CFC11 eq	1.97E-07	1.70E-07	1.08E-07	54.9%	6.95E-08	4.73E-07	3.43E-09
Terrestrial acidification	kg SO2 eq	0.00247	0.002266	0.001	40.5%	0.001096	0.005009	3.16E-05
Terrestrial ecotoxicity	kg 1,4-DCB	1.050833	0.939033	0.498372	47.4%	0.412359	2.398997	0.01576
Water consumption	m^3	0.001112	0.002269	0.016392	1473.9%	0.03951	0.033396	0.000518

Table 2: Uncertainty results for end-point impacts of analysis

Impact category	Unit	Mean	Median	SD	CV	2.50%	97.50%	SEM
Fine particulate matter formation	DALY	5.06E-07	4.62E-07	2.06E-07	40.7%	2.40E-07	1.03E-06	6.51E-09
Fossil resource scarcity	USD2013	0.016632	0.014993	0.007489	45.03%	0.007227	0.036052	0.000237
Freshwater ecotoxicity	Species.yr	1.10E-11	9.05E-12	8.41E-12	76.3%	3.61E-12	3.06E-11	2.66E-13
Freshwater eutrophication	Species.yr	2.13E-10	1.54E-10	1.94E-10	90.8%	3.72E-11	7.49E-10	6.12E-12
Global warming, Freshwater ecosystems	Species.yr	7.73E-14	6.91E-14	3.55E-14	45.8%	3.17E-14	1.71E-13	1.12E-15
Global warming, Human health	DALY	9.38E-07	8.38E-07	4.30E-07	45.9%	3.84E-07	2.07E-06	1.36E-08
Global warming, Terrestrial ecosystems	Species.yr	2.83E-09	2.53E-09	1.30E-09	45.9%	1.16E-09	6.26E-09	4.10E-11
Human carcinogenic toxicity	DALY	8.28E-08	4.14E-08	1.81E-07	218.9%	1.30E-08	3.91E-07	5.73E-09
Human non-carcinogenic toxicity	DALY	1.14E-07	8.32E-08	1.16E-07	102.3%	2.67E-08	3.78E-07	3.67E-09
Ionizing radiation	DALY	8.95E-11	4.74E-11	1.46E-10	162.5%	9.41E-12	3.91E-10	4.60E-12
Land use	Species.yr	7.05E-11	6.27E-11	3.24E-11	45.9%	2.84E-11	1.54E-10	1.02E-12
Marine ecotoxicity	Species.yr	2.26E-12	1.85E-12	1.78E-12	78.8%	7.24E-13	6.48E-12	5.64E-14
Marine eutrophication	Species.yr	3.37E-14	2.99E-14	1.67E-14	49.5%	1.23E-14	7.59E-14	5.28E-16
Mineral resource scarcity	USD2013	0.000513	0.000461	0.000222	43.3%	0.000225	0.001092	7.01E-06
Ozone formation, Human health	DALY	1.94E-09	1.75E-09	8.74E-10	44.9%	8.17E-10	4.34E-09	2.76E-11
Ozone formation, Terrestrial ecosystems	Species.yr	2.78E-10	2.50E-10	1.25E-10	44.9%	1.17E-10	6.20E-10	3.95E-12
Stratospheric ozone depletion	DALY	1.05E-10	9.28E-11	5.30E-11	50.7%	3.88E-11	2.45E-10	1.68E-12
Terrestrial acidification	Species.yr	5.25E-10	4.82E-10	2.13E-10	40.6%	2.51E-10	1.08E-09	6.75E-12

Terrestrial ecotoxicity	Species.yr	1.21E-11	1.08E-11	6.48E-12	53.4%	4.70E-12	2.76E-11	2.05E-13
Water consumption, Aquatic ecosystems	Species.yr	1.97E-15	1.94E-15	1.51E-14	766.7%	-2.86E-14	3.51E-14	4.78E-16
Water consumption, Human health	DALY	2.33E-09	3.96E-09	3.29E-08	1414.0%	-6.99E-08	6.41E-08	1.04E-09
Water consumption, Terrestrial ecosystem	Species.yr	2.52E-11	3.72E-11	2.00E-10	791.7%	-4.18E-10	4.17E-10	6.32E-12

Table 3: Uncertainty results for end-point impacts analysis: Damage assessment

Damage category	Unit	Mean	Median	SD	CV	2.50%	97.50%	SEM
Ecosystems	Species.yr	3.97E-09	3.54E-09	1.79E-09	45.2%	1.68E-09	8.58E-09	5.67E-11
Human health	DALY	1.64E-06	1.46E-06	7.50E-07	45.6%	7.07E-07	3.64E-06	2.37E-08
Resources	USD2013	0.017145	0.015467	0.007701	44.9%	0.007478	0.037304	0.000244